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EFFECT OF OXIDE-COATED CATHODE TEMPERATURE VARIATION IN VACUUM TUBES

WALTER F. JOHNSON

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OF
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IN
VACUUM TUBES

* * * *

Walter F. Johnson

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OXIDE-COATED CATHODE TEMPERATURE VARIATION
IN VACUUM TUBES

by

Walter Franklin Johnson

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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Thesis
J638

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the thesis requirements for the degree of

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ENGINEERING ELECTRONICS

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United States Naval Postgraduate School

J 638

PREFACE

The stimulus to interest in the life and characteristic variation aspects of the vacuum tube fall into three general categories:

a. Tubes for use in inaccessible situations.

b. Tubes for use in equipments employing large numbers of interdependent tubes.

c. Tubes having a higher order of operating stability for use in D.C. amplifiers.

The following three examples serve to illustrate some of the problems at hand and in one case an unexpected solution. (1) During the war years it became the fashion in England for different manufacturers to make tube types to common performance specifications[*,39]. Tests of a popular type of h.f. pentode from three separate manufacturing sources showed extraordinarily wide variations in life span.

Tube type: High transconductance, h.f. pentode with indirectly-heated oxide cathode.

Batch size: 12 tubes.

Life span: Source A 4,000 hours (all tubes)
Source B 1,000-10,000 hours (all tubes)
Source C 40,000 hours (all tubes)

The life spans of batches of a tube type made at different times by one manufacturer were compared: the first batch had a life in excess of 20,000 hours, while the second one, made two years later, had a life

---

[*] Superscripts refer to the bibliography.

of less than 3,000 hours. (2) ENIAC, a high-speed electronic computing machine, has 18,000 operating tubes. Ninety percent of the service interruptions were caused by vacuum tube failures. The life of the tubes used in the ON condition as compared with the same type used in the OFF condition was better by a facter of 50% or more when only the low-emission type failures are considered. Tube lives terminated by low-emission failure averaged more than twice as long as those terminated by failure due to poor cutoff, short-circuited elements and burned-out filaments combined. (3) Considering the UNIVAC tube program, it is seen that reverse grid-current problems were eliminated in the tube type 28D7 by reducing the heater voltage from the rated 28v to approximately 25v[24]. This reduction had no adverse effects in emission or other tube characteristics, since the tube was still space charge limited at 25v, while the cathode and envelope temperatures were lower, providing all around improvement in tube life.

Part of the present interest in these aspects of vacuum tubes is exemplified by two recent papers. One, "Electron-Tube Life and Reliability", by Marcus A. Acheson[1], gives a statistical analysis on tube life. The other, Investigation of Electron Tube Reliability in Military Applications, by Aeronautical Radio, Inc., is a report of a survey of failure reports from the military[2]. This report divides tube failures into two general groups: (1) deterioration failures, due to gradual degradation of characteristics, and (2) catastrophic failures, or sudden major changes in the physical

structure of the tubes. An analysis of tube returns from the military were broken down as follows:

Electrical	28.7%
Mechanical	21.0%
Miscellaneous	18.5%
No defect found	31.8%

It is stated that operating procedures responsible for reduced tube life are: (1) the operation of chassis in standby condition with only the heater on, thus inducing interface formation, and (2) mistuning and poor operation of transmitting tubes and magnetrons.

The results of a survey of modern literature and of a laboratory investigation of the effects of lowering cathode temperature on tube life and characteristics are presented in this paper. The laboratory work was accomplished at Hewlett-Packard Company, Palo Alto, California.

Acknowledgment and thanks are made to Professor Abraham Sheingold of the United States Naval Postgraduate School for his personal assistance, interest and cooperation in preparing this paper, and to Doctor B. M. Oliver, Director of Research, Hewlett-Packard Company for his suggestions concerning the laboratory work.

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CHAPTER I

INTRODUCTION

The objectives of this paper can be divided into two main divisions.

(1) An analysis of the effects on vacuum tubes of cathode temperature changes, with particular attention to:

(a) tube life,

(b) tube characteristics variation, and

(c) tube characteristics stability with time.

(2) The development of a truly short time method of predicting relative tube life.

It is proposed that operation at lower cathode temperatures will have little effect on the characteristics. The fact that interface, a low conductive surface between the core and the coating of the cathode, will grow much slower at lower temperatures, even though its effect will be greater, should mean that the characteristics will be more stable with time. Consequently, failure because of reduced transconductance will be postponed until a later time. Lower temperature at the cathode will mean lower envelope and heater temperatures with a reduction of filament burn-out and gassy tubes. It will mean an increase in susceptibility to poisoning, but this being an early life phenomena, it should be discovered quickly and thus have little bearing on errors in choosing long-life tubes. Cathode coating evaporation should also be decreased with lower temperature

as should tube noise.

A rapid determination of cathode temperature should enable one to predict a relative life expectancy on this basis alone; this being based on the information that absolute cathode temperature is, to date, not a design factor. At the present time the design of tubes is based on heater watts per square centimeter of cathode area. In the practical case this figure may vary from 1.8 to 4.2 watts per square centimeter, the exact value being determined by the intended use of the tube. A short term test, less than 1000 hours, whereby samples from each lot of tubes are induced to grow interface should give a relative indication of their susceptability to this growth and thus an indication of expected life from this point of view. Measuring the emission capabilities before and after this test should give an indication of the degree of activation and degassing of the tube and thus enable a prediction of life expectancy on the basis of emission. It is not proposed that the above tests will facilitate an absolute prediction of life expectancy, but that they will provide a basis of chosing tubes for use in critical circuits and locations, a situation which is not now existant.

The following section will give a resumé of existing information on the activation, emission and conduction of an oxide-coated cathode. Emphasis will be placed on particular events upon which tube life and characteristics are dependent. The complete physics and chemistry of the above processes will not be presented, but most available information of this nature is included in the references[17].

The complete process of emission is a complicated superposition of distinct effects which are complex in themselves, difficult to separate, and possible to study effectively only in isolation. Its study involves physics, chemistry, semi-conductor theory, electrolysis and thermodynamics. As will be indicated, there is still discussion as to some of the characteristics of emission.

Following the above section a discussion of the factors affecting tube life is presented, after which are given the results of several investigations on the variations of tube characteristics with changes of cathode temperature.

A laboratory investigation of the effects of varying cathode temperature was carried on in conjunction with the above survey of existing literature. Methods of testing are given in the section on testing procedures. Following, a detailed description of the laboratory procedure is given along with the results and a discussion of the results.

CHAPTER II

HISTORICAL RESUMÉ OF OXIDE CATHODE PROCESSES

1. Emission and Conduction

Basically the conventional model of the oxide cathode usually used is one in which the oxide is regarded as a "reduction" semiconductor of the n-type carrying an excess of the electro-positive elements, donors. The excess elements are barium and strontium metals which are bound in the disturbed lattice of barium-strontium oxide in such a way that they are not subject to free evaporation at normal running temperature (approximately 1000°K). The presence of donors serve to increase the conductivity and to decrease the work function of the coating so that electron emission is practicable at reasonable temperatures. The oxide cathode was invented in 1903 by A. Wehnelt[66, 67, 68]. At that time and until the last decade failure of vacuum tubes was mainly by filament burn-out and as a result little interest was taken in the process of emission. With the production of high vacuums, the problem of filament burn-out lessoned and a major cause of failure became related to the process of emission.

The process of emission consists of the production of donors along with free electrons, mainly at the core surface, the migration of the donors through the coating due to ionic conduction with the resulting reduction of internal work function, and the flow of free electrons through the coating to be emitted. It is to be noted

that whereas the internal work function decreases, the external work function remains constant[23].

According to the Loosjes-Vink theory there may be three mechanisms of electron conduction in the oxide-coating: (a) conduction by an electron gas in the pores or conduction through the grains limited by contact potential barriers between grains, (b) pure conduction through the grains, and (c) surface conduction through surface barium layers[31, 42]. All of these are connected in parallel in the most general case, and the monoatomic surface layer of barium serves to reduce the work function. It has been found experimentally that, independently of the stage of activation, the log σ vs 1/T curves can be divided into three parts (σ being the conductivity of the oxide coating): in Part I, up to 800°K, the temperature dependency is rather low, and in Part II (800 - 1000°K) it is much higher, while at still higher temperatures ($>$ 1000°K, Part III) it drops again[31]. The temperature range in which the Current-Voltage characteristics have been measured can be divided into the same three parts: up to 800°K they are linear, from 800 - 1000°K they are curved towards the V-axis and above 1000°K they are again linear. In explaining these facts, one has to do essentially with two of the above conduction mechanisms. Considering the electron conduction through the particles of the oxide coating, the conductivity corresponding to this mechanism will be low, though the real conductivity in the BaO-SrO grains may be high, because the surfaces where the crystalline particles touch one another are very small.

This mechanism applies to Part I of the temperature region; here the activation energy varies from 0.6–0.9 eV with increasing cathode activation.

The other mechanism is the conduction through the electron gas present between the emitting grains of the porous oxide coating. If the density of the electron gas is great enough ($T > 800^{\circ}K$) then the pores between the grains become conducting, so that, parallel to the mechanism of Part I, another mechanism of conduction is then started, the properties of which will depend entirely upon the properties of conduction in an electron gas present in the pores. The activation energy of this second conduction mechanism (for $T < 1000^{\circ}K$) is substantially the same as the energy corresponding to the work function of the coatings at all degrees of activation (2.2-0.8eV)[22,26,32,53,54,60,72].

Figure 1 gives the physical configuration of ions and atoms at the surface of the cathode.

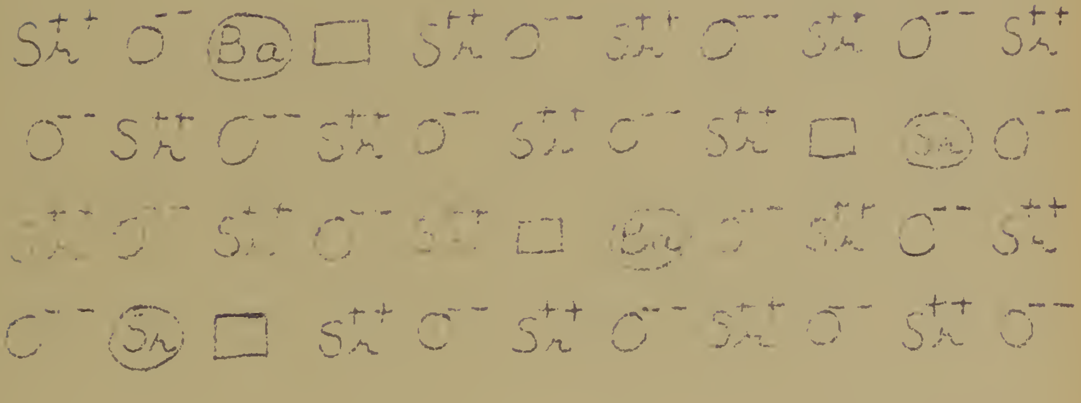
The chemical process of free barium production from the oxide is given as

$$Si + 2BaO \rightarrow SiO_2 + 2Ba.$$

The typical core metal is nickle plus 0.05% magnesium and 0.05% silicon[40].

The free barium-strontium layer on the surface of the coating is constantly being depleted at a rate proportional to the cathode temperature by evaporation and by chemical recombination[10,70]. It must continually be reformed to provide a low work function which,

Configuration of Ions and Atoms at the Surface of the [BaSr]O Cathode[23]



Sr^{++} O^{--} Ba □ Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++}

O^{--} Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} □ Sr O^{--}

Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} □ Ba O^{--} Sr^{++} O^{--} Sr^{++}

O^{--} Sr □ Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} O^{--} Sr^{++} O^{--}

□ = Vacancies

Figure 1

in turn, allows ready liberation of free electrons. Barium evaporates from this monolayer more readily than strontium at operating temperatures and it deposits upon the grid wires to cause grid emission. The evaporation energy or temperature of strontium on strontium-oxide is lower than that for barium on barium-oxide. However for the barium-strontium layer in barium-oxide--strontium-oxide mixed crystals, the barium apparently boils off more easily.

The energy of the electron beam is believed capable of decomposing films on positive electrodes. These are fundamentally barium-oxide compounds evolved during coating decomposition and activation. When the SrO^{--} negative ions are liberated by the electron beam energy they react easily to form compounds with the layer of Ba^{++}-Sr^{--} reducing the activity of the cathode surface layer.

Experimentally Nergaard[44] has concluded that:

(1) Current flow decreases the conductivity of the oxide at the positive boundaries.

(2) The increase in conductivity between the base metal and a cathode probe with increasing current shows that whatever decreases the conductivity at a positive boundary increases the conductivity at a negative boundary. Thus a reasonable inference is that donors are transported electrolytically from the positive boundaries toward the negative boundaries.

(3) Changes of conductivity vs time indicate an ionic phenomena.

Because of the instability of barium and strontium oxide under atmospheric conditions the carbonate of the above is coated on the base metal of the cathode and then reduced by heat in a vacuum to the oxide. In order to facilitate the production of excess barium and strontium a relatively inactive metal, polluted by an added reducing agent which acts as a catalyst, is used as the core of the cathode. It is found that in an active cathode a fraction of the order of 0.5% of the oxide molecules has been reduced to free barium, strontium. This core metal as mentioned above is usually nickle and the reducing agents are magnesium and silicon.

With the base metal coated with the carbonate and heat applied in a vacuum, the rate of activation of the cathode is accelerated if an electron current is drawn from it. This suggests that an electrolytic current passes through the oxide and liberates free barium and strontium[9]. Harris has detected barium and strontium which actually penetrated the core of an oxide cathode from which a heavy current has been drawn. When the cathode was merely glowed without drawing current, no barium or strontium was found in the core. If, on the other hand, the direction of the current through the oxide is reversed by supplying electrons to the cathode from an external source electrolysis should result in deposition of a layer of free barium on the surface of the oxide. Essentially the same changes in activity should be observed as when barium is deposited from an external source. Becher and Sears have shown that this is

the case[9]. They were further successful in showing that the rate of appearance of barium at the surface is proportional to the quantity of charge sent through the oxide. Becher concluded that about 0.4% of the current at 800°K is carried by barium ions in the oxide. The above process of barium formation is fundamental to the continued operation of the cathode. It is purposely accelerated during the initial activation, but it also continues throughout the life of the cathode. The operation under very reduced cathode current restricts the activation and causes loss of emission. This has been known as "sleeping sickness", and is a major problem in OFF-ON computer work. The following table shows the results of increasing the current on available saturation current[62].

Operating Temperature	1075°K			900°K	
Emission Density	10ma/cm^2		45ma/cm^2	10ma/cm^2	45ma/cm^2
	A	B			
	ma	ma	ma	ma	ma
I_s at 0 hr.	1.17	1.14	1.19	1.00	1.35
I_s at 300 hr.	0.88	0.09	1.36	1.07	2.37

Note: Nickle sleeves with A having 0.2% Fe
B having 0.4% Fe

Data taken shows that an increase in current density by a factor of more than twenty has no detrimental effect on the cathodes examined.

The following is a summary of the processes, less electron conduction, which occur in the coating[23] (reference Figure 2).

A. Processes occurring at the boundaries of the oxide coating:

(1) Processes at the oxide-coating-vacuum boundary where a distinction must be made between,

Cross Section through a fully activated Oxide Coating[23]

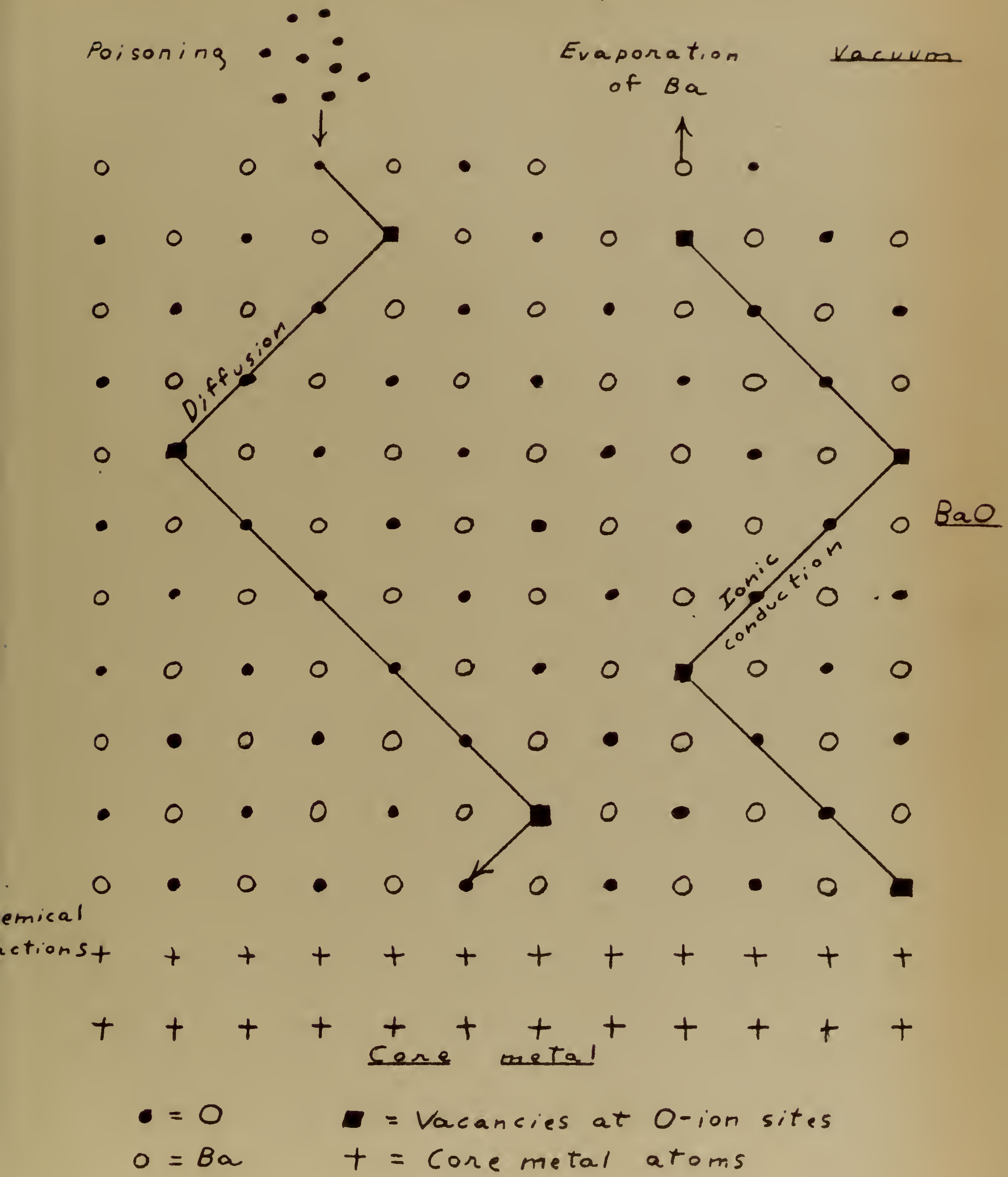


Figure 2

    (a) evaporation of excess Ba-atoms from the surface;
    (b) emission of ions from the surface;
    (c) chemical reactions at the surface occurring between the excess barium and residual gases (poisoning of the cathode)

  (2) Processes at the oxide-coating-core-metal boundary; chiefly chemical reactions with barium oxide.

B. Processes occurring in the interior of the oxide coating by which the number of vacancies and excess barium atoms in the coating is altered, namely:

  (1) Ionic Conduction, and
  (2) Diffusion.

2. Interface

In the examination of the cathode of a spent tube, inspection may reveal that all the oxide has disappeared, but frequently the cathode will be found to present much the same appearance as it did at the beginning of its life. An investigation of the characteristics of the tube may indicate a reduced value of transconductance, and a poor current response to an applied microsecond grid pulse (an exponential decay with a time constant in the order of a microsecond of plate current from an initial value to a lower quiescent value). These effects have been historically attributed to a low conductive surface between the core and the coating called interface and/or a physical separation between parts of the coating and the core.

Interface has been identified with barium orthosilicate[52]. Its chemical creation is as follows:

$$Si + 4BaO \rightarrow Ba_2SiO_4 + 2Ba$$ [11]

$$SiO_2 + 2BaO \rightarrow Ba_2SiO_4$$ [39]

It forms as a hard compact layer of a few microns thickness between the core and the matrix. Its behaviour is that of a semi-conductor and the equations above indicate the probability of barium being the activator.

The physical thickness of the layer once established does not increase to any great extent with time[11,65]. This has been disputed by Eisenstein[18]. The rise of resistance is ascribed to an increase in the specific resistivity of the layer rather than to its physical

growth; in short, the resistance growth is regarded as a deactivation phenomena of a semi-conductor.

Because of the extreme thinness of the interface layer (10^{-3} cm with lattice constants a=5.7, b=10.0 and c=7.5 angstrums, Eisenstein[18]) a considerable capacitance exists as a shunt across the resistance, and the effect of the interface layer on tube performance is anologous with that of a bias resistor and a shunt capacitor inserted in the cathode lead. The values of these components are suspected of varying with some function of frequency, the exact nature not being known at this time[21]. The values of the resistance will vary from tenths of ohms to thousands of ohms per square centimeter of cathode area[44]. The capacitance will vary between 5000-20,000 uuf, thus giving a time constant of the order of one microsecond[63]. It has been suggested that the single R-C network is too simple and that actually it should consist of a series of parallel R-C networks[43].

At first sight it would appear that interface resistance is of no consequence in high-frequency applications. This is only true provided the cathode current is maintained constant, since the growth of resistance will normally cause a reduction in the operating cathode current and hence a fall in transconductance. The appreciable negative temperature coefficient associated with the interface degrades the transconductance/heater supply characteristic and may cause trouble in stable amplifier design[11].

The rate of interface resistance growth is inversely proportional to the cathode area and varies exponentially with the absolute

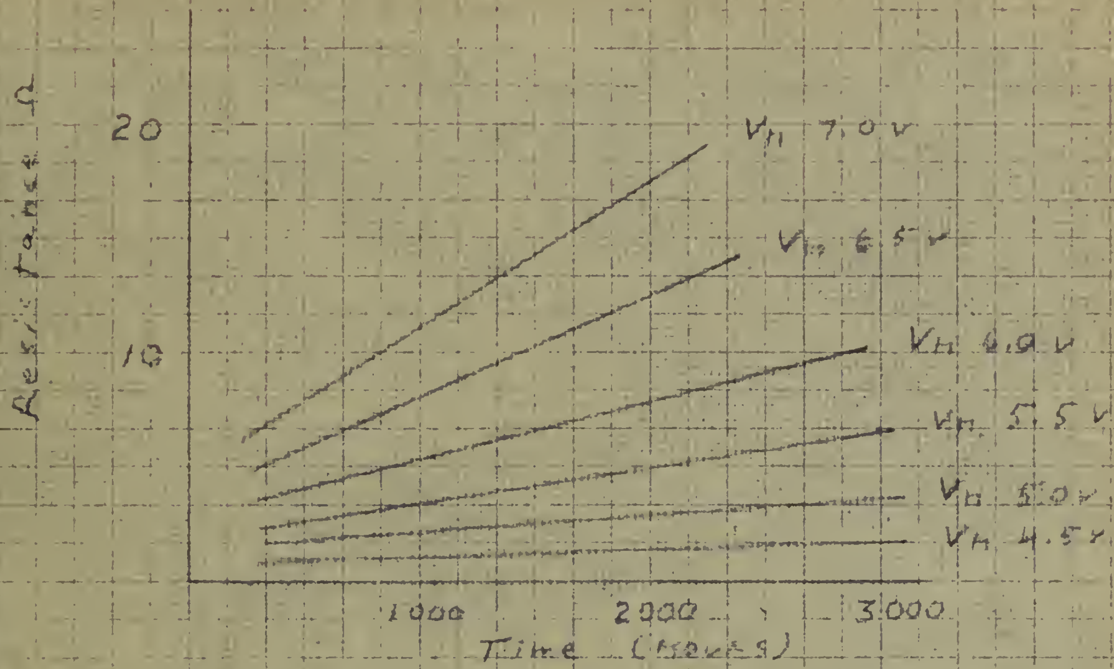
temperature. The value of interface resistance varies exponentially with the reciprocal of the absolute temperature[11] (Figures 3 and 4). The resistance increases with life, as indicated, while the capacitance decreases; thus there is little major change in the time constant[50].

Many studies of the rate of interface growth as a function of core impurities have been made[47]. Child has reported that a batch of cores with only 0.005% Si (0.05% Si normal) show that the rate of growth was on the average only 1/7th that of normal[11].

It has been experienced that the interface can be partially reactivated with electron and ion flow. As the cathode is aged, the layer of barium orthosilicate thickens to the point where reaction between the silicon of the core and the barium oxide of the coating becomes negligible[65]. The behavior of the concentration of donor centers in the layer during the aging will depend on whether an electric field is present, because the donor centers behave on the average as positive charges.

If no electron emission is drawn from the cathode, there is no electric field in the interface region, and the donor centers can migrate out of the layers of interface compound by thermal diffusion. The concentration of donor centers in the layer is reduced to the extent that it is insufficient to maintain a negligible resistance; the cathode has then developed an interface resistance. If the cathode is aged under conditions of cathode current flow,

Growth of Interface Resistance at Various Cathode Temperatures[11]



Relative Rate of Growth of Interface Resistance with Temp.[11]

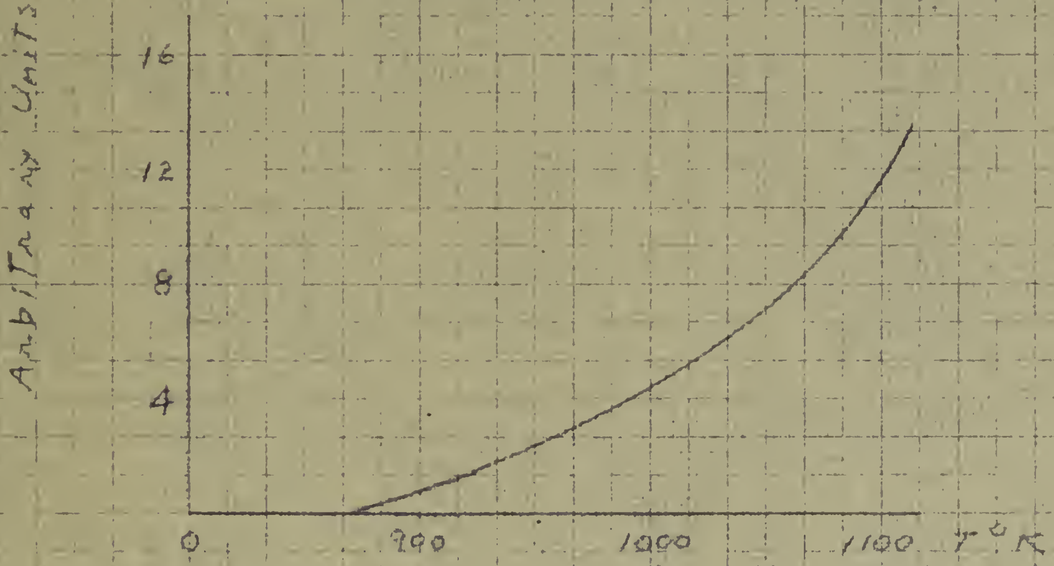


Figure 3

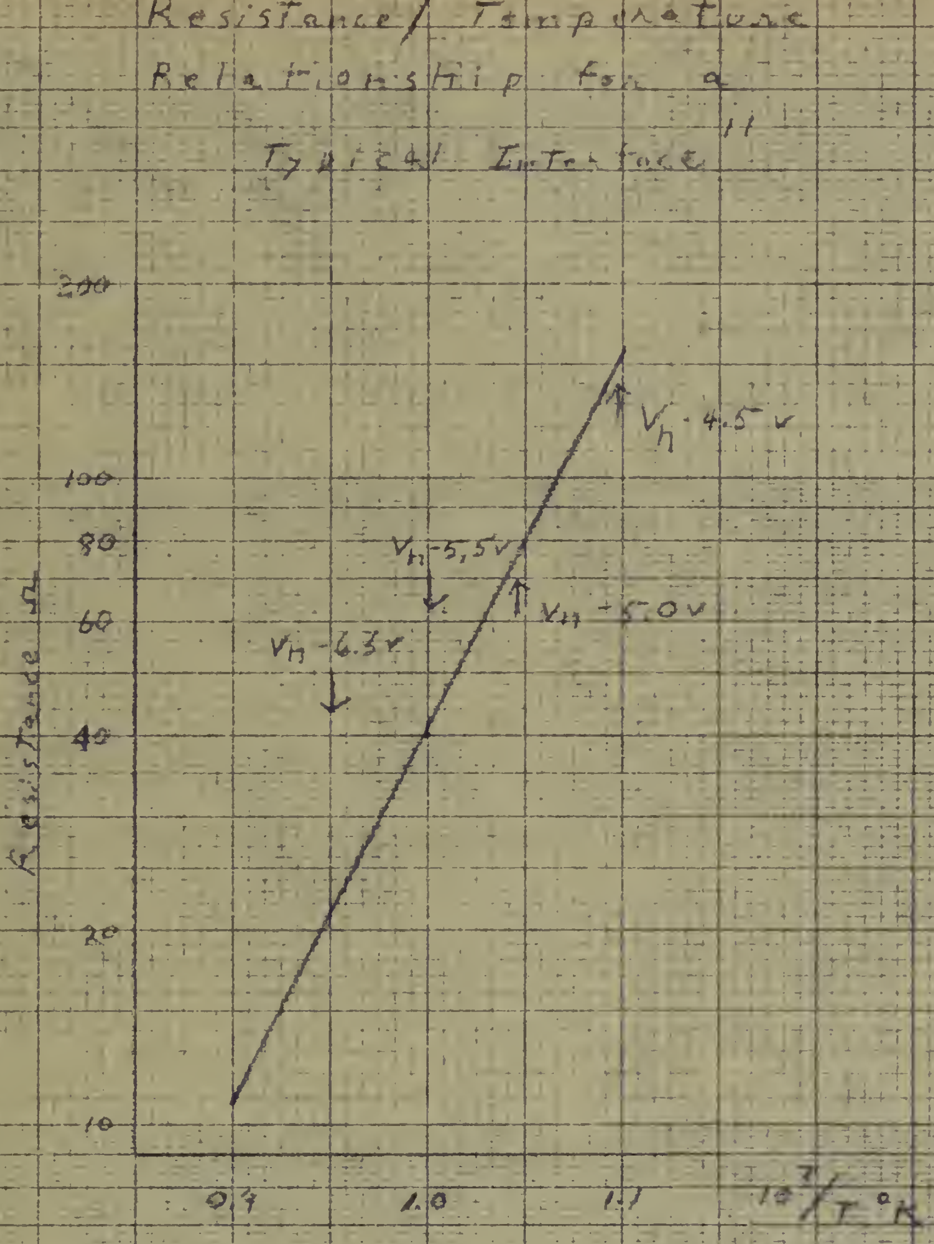
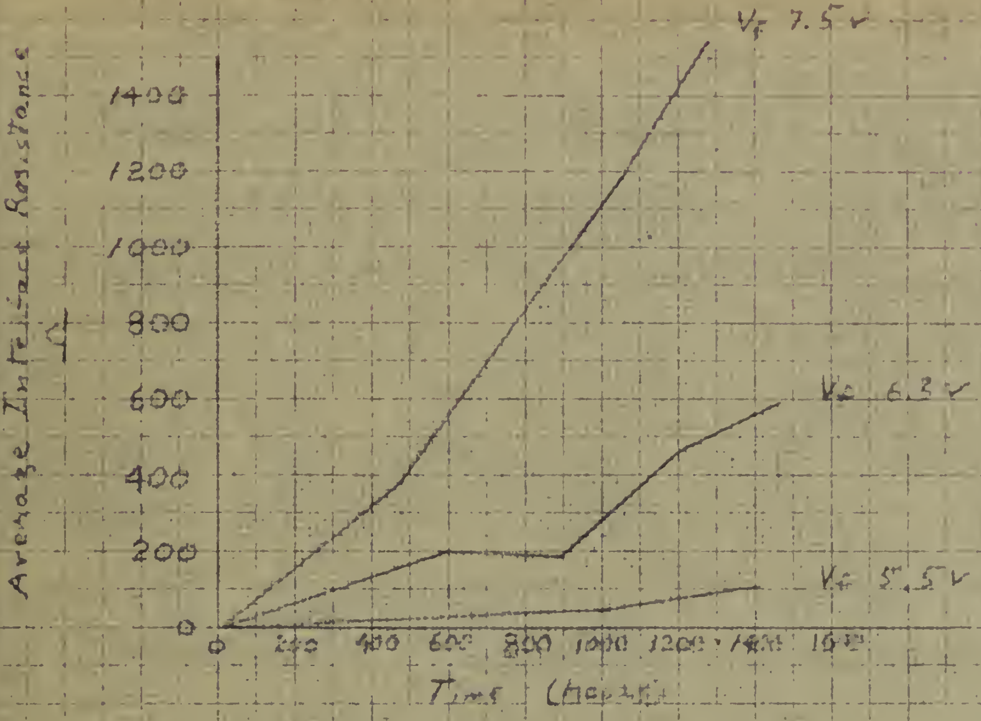

Resistance/Temperature
Relationship for a
Typical Interface"
200
100
80
60
40
20
10
Resistance Ω
0.9
1.0
1.1
10³/T °K
Vh-4.5v
Vh-5.5v
Vh-5.0v
Vh-6.3v

Figure 4

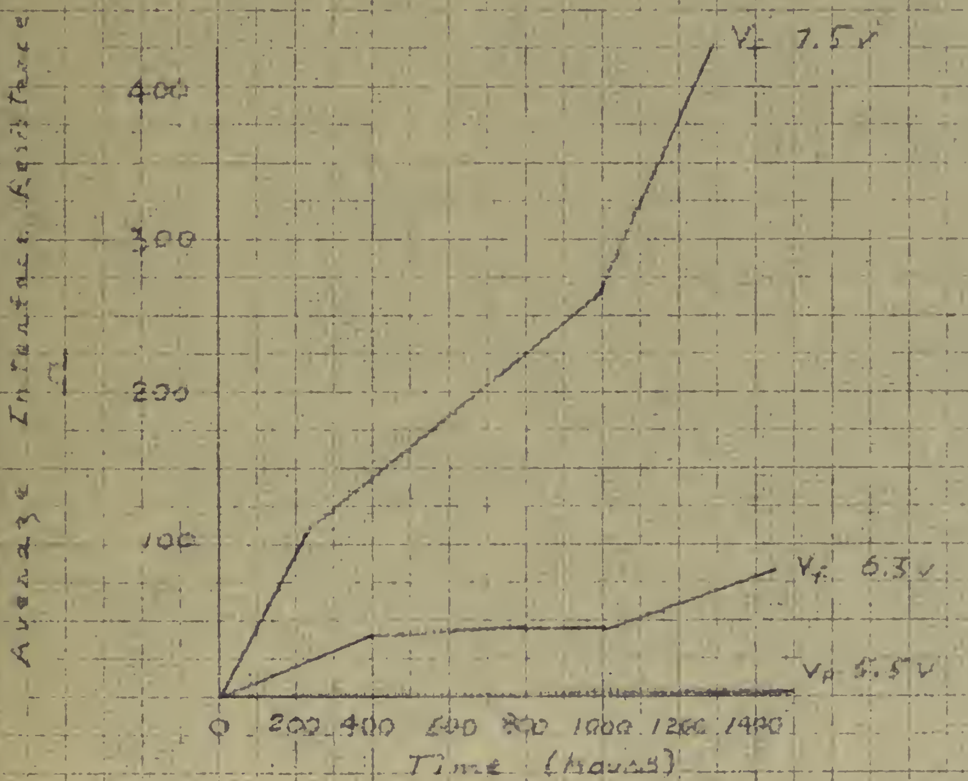
an electric field directed from the oxide to the core exists in the interface region. Field-induced migration of donor centers into the layer of interface compound and thermal diffusion of donor centers out of the layer of interface compound are then in competition and the equilibrium concentration of donor centers in the barium orthosilicate layer is greater than it would be if thermal diffusion were the only migration process. If the field is strong enough, the equilibrium concentration of donor centers is sufficient to maintain the conductivity of the interface compound; the cathode does not develop an interface resistance. This equilibrium concentration of donor centers and consequently the conductivity will vary as does the field and cathode current and thus the interface compound can be partially reactivated. Figure 5 shows the effect of plate current flow on the growth of interface resistance. Eisenstein attributes this reactivation solely to the thermal effect of cathode current rather than to the combination of thermal and electric field, the production of donors being proportional to temperature[20].

The observance of interface effects have been made by Matheson[33], Eisenstein[20] and Mutter[41], to name but a few. Deb[12] has attributed the pulse decay phenomena partially to oxide poisoning, but this is probably only a minor effect. Wright[71] has attacked analytically the problem of an analog network. Herrmann[23] has attributed the observed rectification effect to the interface in accordance with its variation of conductivity with ion migration direction. Nergaard[45] has surveyed the different procedures for measuring interface

Rate of Growth of Interface Resistance



Operation Under Cutoff Conditions



Class A Operation

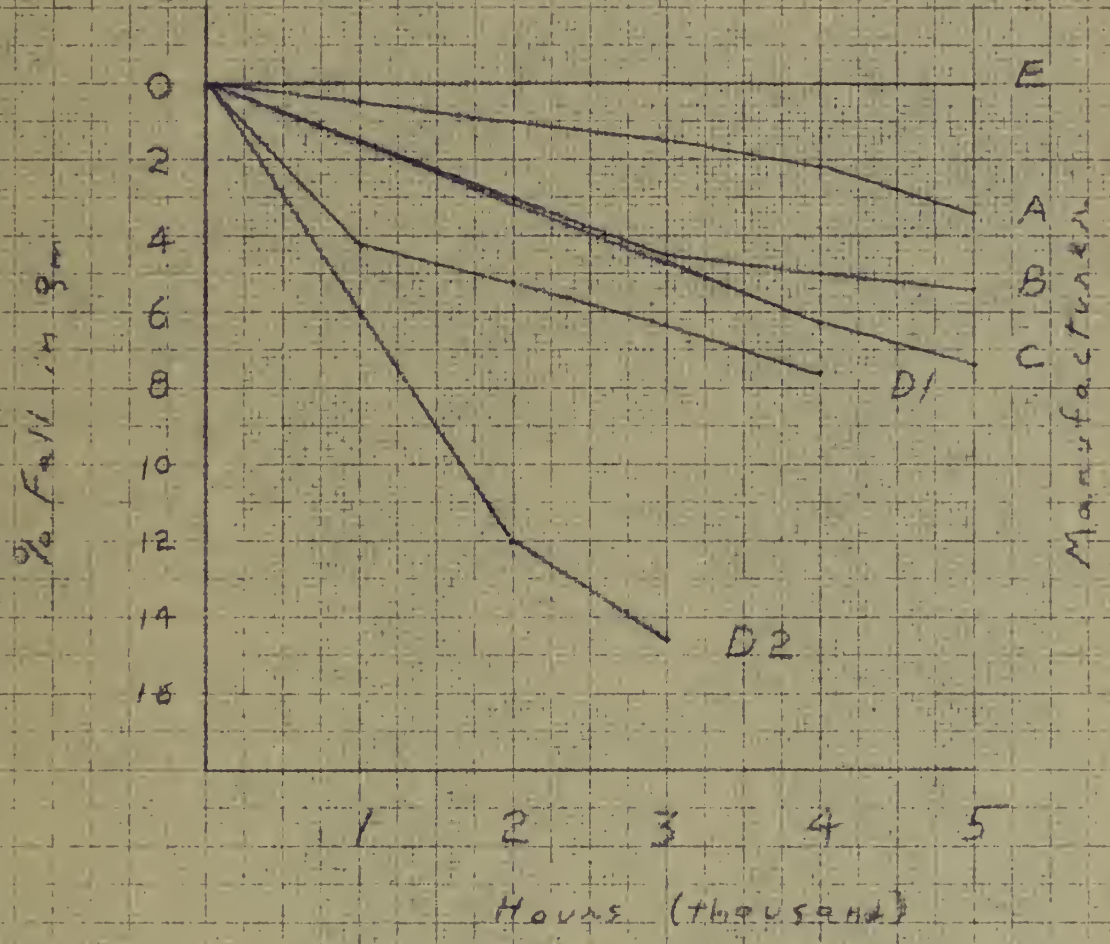
Figure 5

resistance. Along with the above he concluded, from life-test data on tube types 6SN7-GT and 6SL7-GT operating in time-division-multiplex terminal equipment, that (a) the interface resistances increase rapidly with time during the first 8000 hours and then show a tendency to saturate and (b) the "final" resistances are about in proportion to the original silicon contents of the core metal.

Raudorf[48] sought to attribute interface to actual physical separations between cathode core and coating. While this theory has not been received with much attention, it is presented with apparent factual backing. It is further discussed by Raudorf[49] and Eisenstein[19],

Metson[40] has related the fall in transconductance with interface resistance (Figure 6). Similarly Eaglesfield[15] has shown that where the interface resistance grows rapidly, on the basis of transconductance decay, the tube life is apt to be short, and, where the interface resistance grows slowly, the tube life is apt to be long. In his tests the values of interface in all tubes tested reached a common value of approximately 40 ohms per square centimeter and did not increase thereafter.

Fall in g_m due to Interface alone for CV138 Type Valve[40]



$t = 0$ $R_{interface} < 1\Omega$

B, C, D1 typical

E Platinum-cored oxide cathode + no silicon

Figure 6

3. Poisoning

Chemical processes on or in the oxide coating, producing an increase in work function and a decrease in emission, are called poisoning processes. Poisoning at the boundary with the vacuum is produced by residual gases which either remain in the tube when it is sealed off, or which are given off during operation from components of the tube which were insufficiently degassed or cleaned. Such a residual gas will poison the cathode if it attacks chemically either the excess barium or the alkaline earth oxide of the coating and changes these into some other chemical compound. The poisoning phenomena will depend on the composition of the residual gas, on its pressure, on the temperature of the cathode and on the voltages applied to the tube[23]. The products of surface poisoning have been identified as mainly BaO, SrO, $BaCl_2$, $SrCl_2$, $BaSO_4$ and $SrSO_4$[36].

The most important of the poisoning gases is oxygen, and for the oxygen ions three main sources exist[54].

(1) The surface layer of oxygen, from which negative ions are normally formed by positive bombardment. These ions are characterized by the possession of excess energies.

(2) The interior of the coating. Ions are formed in this region during recovery periods from oxygen which has diffused into the coating during poisoning.

(3) The space in front of the cathode, which supplies

an appreciable proportion of the ion beam only in the initial stages of recovery.

These oxygen ions may decrease the excess barium in the coating simply by occupying vacant oxygen sites in the crystal lattice. At moderately high oxygen pressures or low cathode temperatures this poisoning is irreversible. The original emission can be recovered only by reactivating the cathode at a higher temperature. At low oxygen pressures and normal cathode temperatures the poisoning is reversible[50]. The reverse process of poisoning is the emission of oxygen ions from the cathode and this may be assisted by a favorable potential gradient produced by the passage of a cathode current[35]. Current flow appears to effect only the rate of recovery, but the cathode will be more resistant to poisoning at higher current densities.

The following are the results of a poisoning study reported by Shephard[53].

(1) Poisoning phenomenum was completely reversible.

(2) Emission of ionized oxygen from the cathode increased immediately after recovery commenced.

(3) Higher activation-rates existed in the presence of larger potential gradients in the cathode coating.

(4) (a) Increased sensitivity to poisoning at low temperatures was observed;

  (b) Considerably higher rates of oxygen evolution resulted during recovery at higher temperatures.

(5) Reduction of emission resulted by either (a) the formation of surface oxygen films or the emitting oxygen crystals, or (b) the occupation of vacant oxygen sites (especially near-surface sited) in the oxide crystal lattice.

It is to be noted that evidence in support of the Loosjes-Vink theory of conduction is most readily obtained by experimenting with oxygen poisoning[34]. The procedure of injecting oxygen ions into an oxide at various oxide temperatures and noting the change of conductivity was generally followed. Where the conduction was mainly from crystal to crystal, the oxygen had little effect, but where it was through the intercrystal spacing, the oxygen had much effect.

The release of oxygen during activation can result in heavy contamination of the anode[12]. Subsequent release of this oxygen under electron bombardment may lead to a sudden increase in gas pressure in the tube to 10^{-6}-10^{-7} mm Hg from a normal of 10^{-6}-10^{-9} mm Hg. This being far above the equilibrium value for oxygen in the cathode, rapid deposition on the cathode becomes possible. A reduction of electric field potential with a consequent decrease of electron energy results in a decrease in the poisoning of the cathode by this means.

Another major source of poisoning gas is the mica used in the tube. Holland[25] has reported this effect and presents evidence that the poisoning potential of mica varies with the source of supply for the mica.

The degree of poisoning effect on the reduction of emission is

proportional to the residual gas pressure of the tube. As the tube is aged, the residual gas is absorbed by the tube elements and the gas pressure is reduced to values in the order of 10^{-9} mm Hg. The cathode, being of moderate surface area and operated at a high temperature, is the element most receptive to the absorption of this gas. Consequently a measure of residual gas pressure in the tube is indicative of the degree of poisoning of the cathode.

Metson[39] developed a method whereby a multi-electrode tube is capable of measuring its own residual gas pressure. The passage of electrons from cathode to anode results in the formation of positive ions whenever an electron makes a suitable encounter with a wandering molecule or atom of residual gas. Such positive ions migrate to the negative control-grid and cathode and set up a reverse grid-current. He has expressed the gas pressure indirectly in the form of a vacuum factor, "k", where:

$$k=I_{rg}/I_{a} \text{ uua/ma}$$

I_{rg} -- Reverse grid current in uua

I_{a} -- Anode current in ma

A simple proportionality exists between the pressure "p" and the vacuum factor, namely

$$k=cp$$

A plot of "k" vs time shows a decrease from an initial value to a constant value "k_0" (Figure 7). The integral of the area under this curve, $\int_0^{\infty} k\,dt$, the gas integral, is a measure of the ionized

Change of Vacuum Factor "K" with Time for
50
Type 12AX7 Tube

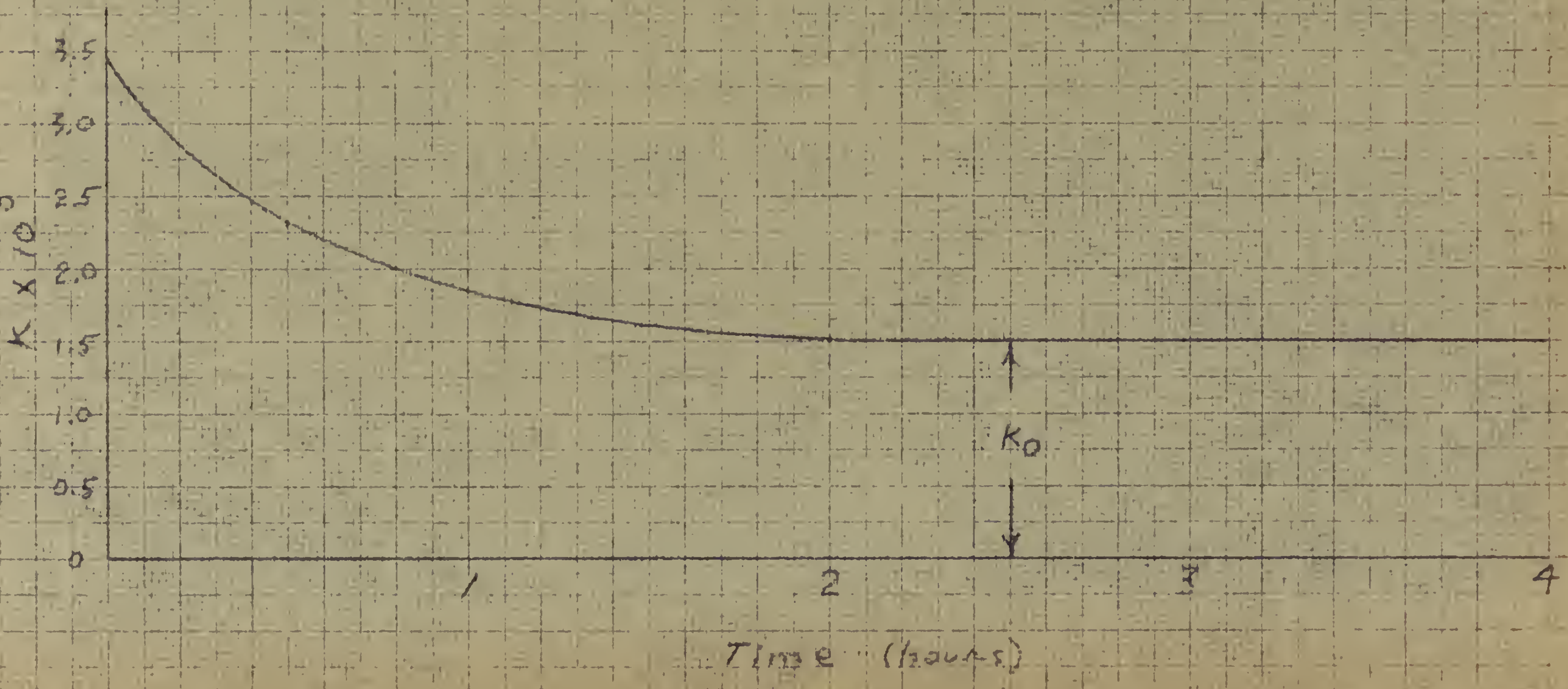


Figure 7

gas which is driven into the cathode. A comparative study of two batches of a common tube showed that the short-life batch (approximately 3000 hours) had a large gas integral whereas the long-life batch (approximately 25,000 hours) had a small one. Investigation has shown that the factor is defined completely as a function of anode voltage, anode material and physical size of the positive-ion collector. It is interesting to note that under comparable operating conditions the value of "k_o" for different tube types was constant. Further discussion of the vacuum factor as to the conditions upon which it is dependent is given by Metson[37,38].

4. Evaporation

At normal cathode temperatures, the oxide matrix is subject to thermal evaporation. The rate of evaporation decreases considerable in the order barium-oxide, strontium-oxide, calcium-oxide. It also decreases with time because the barium-oxide evaporates preferentially from the superficial parts of the coating and is not sufficiently replaced by diffusion from the interior. Hermann found that the rate of evaporation of barium-oxide is independent of the type of basic core metal used[23], and Wooten[70] points out that the reducing agents in the basic core metal are important to the rate of evaporation.

The rate of evaporation of the oxides of barium, strontium and calcium follow the usual exponential increase with temperature[39]. The table below gives an indication of the rates involved.

Temperature	Evaporated Quantity	Time for evaporation of 1 mg/cm^2
Degrees K	$mg/cm^2/hour$	hours
1100	8×10^{-5}	12,500
1000	1.25×10^{-6}	800,000

If a coating weight of 5 to 10 mg/cm^2 and cathode temperature of 1200°K are assumed, the time during which half of the coating would evaporate is found to be between 1000 and 2000 hours. At a temperature of 1000°K this figure is 1,000,000 hours. Bulk loss by evaporation of barium and strontium may be more serious than the above. Experimental evidence has indicated that a barium-strontium-

oxide matrix supported on a core carrying reducing agents may lose that weight which is chemically equivalent to the total weight of the effective reducing agents in the core[39]. Calculation shows that 10-20% of the useful matrix might be lost in this way with core nickels commonly used in industry.

The following rates of barium evaporation have been measured[23].

1200°K	1400°K	
0.1	14	ug/cm^2/hour

Wooten has recently reported the following results[70].

(1) The product evaporated from commercial type cathodes under normal conditions is largely Ba metal; less than 5% is Sr; less than 2% is BaO; and less than 0.01% is SrO (Figure 8)

(2) Chemical reducing agents in the support metal are important in determining the rate of Ba evaporating during life.

(3) Anode and grid composition affects the rate markedly. This is especially true for the evolution of Ba during exhaust.

(4) There is (a) no correlation between the rate of Ba evaporation and thermionic activity of individual cathodes, and (b) no effect of space current on the rate of Ba evaporation.

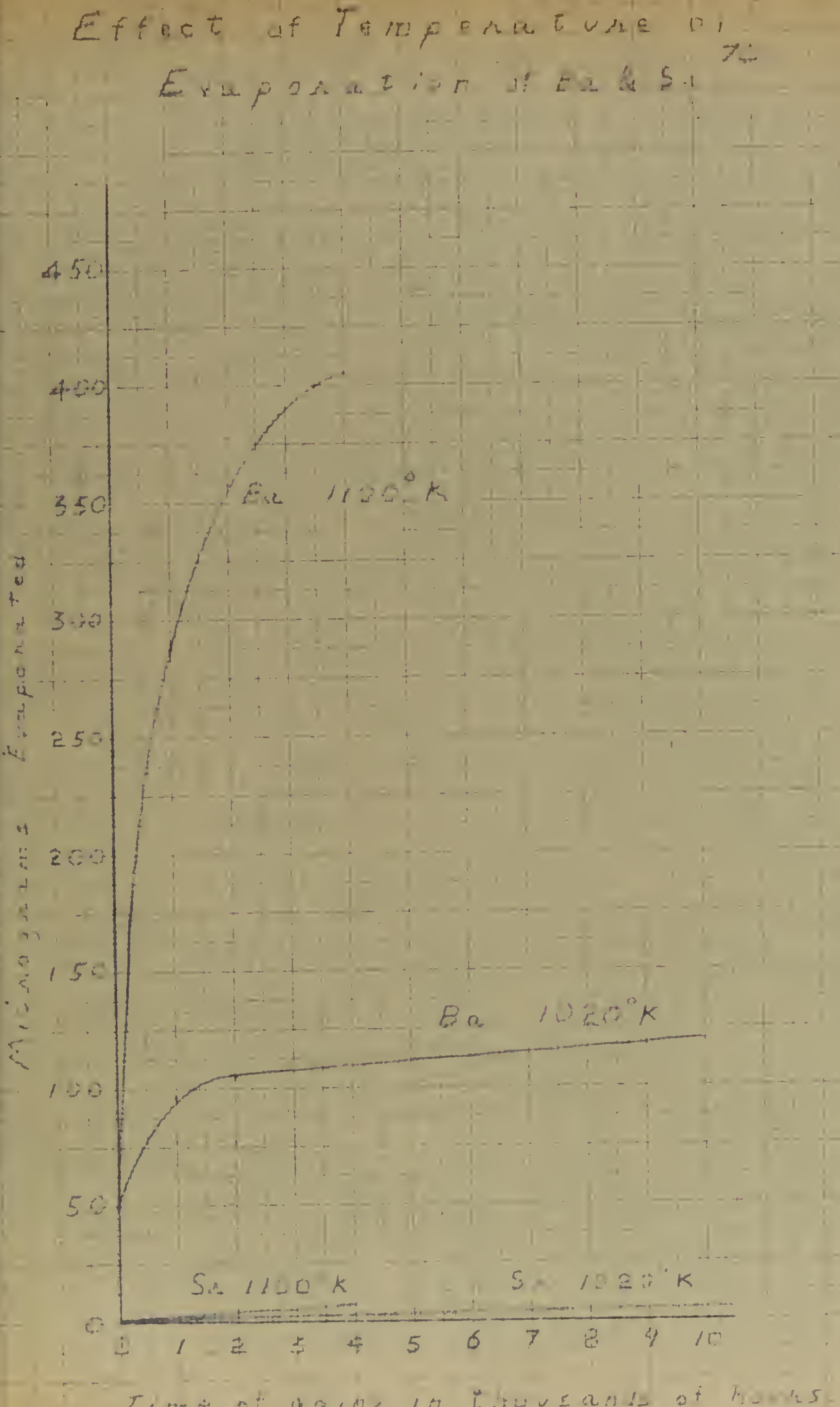

Effect of Temperature on
Evaporation of Ba & Sr
Micrograms Evaporated
450
400
350
300
250
200
150
100
50
0
Ba 1100°K
Ba 1020°K
Sr 1100°K
Sr 1020°K
0
1
2
3
4
5
6
7
8
9
10
Time of aging in thousands of hours

Figure 8

5. Sparking

Stereoscopical X-ray shadow images of carbonate coatings has shown that they are not uniform, but consist of a loose conglomeration of particles of an irregular shape with interspaces of different size[23]. The mechanical strength of such a coating is much smaller than that of a homogeneous material, and consequently if a high electric field is applied to the cathode, the electrostatic force may tear from the cathode particles which are then attracted by the electrode producing the field and which will hit this electrode with a high velocity. This may give rise to the formation of an arc and to the destruction of the cathode.

If the current drawn from the cathode is increased, the areas which emit the most and supply high current densities are heated up. The emission current from these areas will therefore rise and the differences in emission between high-emitting and the low-emitting areas will become even more pronounced. If this process continues the temperature of the high-emitting areas will finally increase so much that considerable evaporation of the coating will take place from these areas with the evolution of appreciable quantities of gas. The ions produced during this process will then tend to annul the negative space charge in front of the cathode, and the field strength there, which is negative under space-charge conditions, will become positive. Finally the particles of the coating will be removed by evaporation, by sputtering produced by the ions, and by electrostatic forces trying to tear the particles from the coating. This phenomenum is called sparking.

It has been found that the critical current density at which the sparking starts is displaced to higher values, if the temperature of the cathode is raised or the activation improved. The sparking phenomenum is always much stronger at low cathode temperatures, because the differences in emission between different areas of the cathode are larger at these temperatures. Furthermore, the cathode, when operated at sufficiently low temperature, emits a current which is nearly saturated, and a high positive field strength in front of the cathode will be obtained more easily than with high temperatures. A non-uniform interface will aggravate this sparking.

6. Noise

Noise, as described here, refers to the Johnson effect in the cathode coating and shot noise in the vacuum. A division of shot noise is called "flicker noise" and its only identifying characteristic is its upper frequency limitation of around 10KC. The general theory of Johnson noise[55] applies. Flicker effect is explained by a surface phenomenum. With reference to shot noise, Blewett, in quoting Szepesi, points out that a variety of effects contribute toward making it increase rapidly if the cathode is operated above or below the temperature range of 875-1050°K[9].

Amakasu reported the following results as applied to Johnson noise[3].

(1) Excess noise generated by the flow of current is proportional to the square of the current flowing through the coating layers (Ba-Sr oxide coating).

(2) The noise is greatly affected by the activation of the cathode, a slight decrease in activation causing a sudden increase of noise.

Along the same line, Hannom has reported that flicker noise resistance due to the interface effect varies as the cathode current squared[21]. Hannom is supported in his theory of attributing flicker noise to interface resistance by Berktay[8] and Lindemann[30], the latter adding that a minimum noise was experienced with a 100ua current. Tomlinson[59] and Blewett[9], however, have definite ideas attributing it to a surface effect. Their theory relates flicker noise directly to mobile

islands of activation on the surface. Following this view, flicker noise should be proportional to cathode temperature. This variation with temperature is substantiated by Herrmann[23] who reports that flicker effect, due to fluctuations of the work function of the cathode (Johnson) or fluctuations of the emission with ionic current accompanying the emission current (Macfarlane), would increase with increasing temperature. Thomlinson, however, has reported that flicker noise should increase above and below the 1000-1100°K range[58].

As seen above, various kinds of results of noise study have been reported. It is believed that basically noise should generally decrease with increasing degrees of activation and decreasing temperature.

CHAPTER III

TUBE LIFE STUDY

With the development of modern electronic devices using hundreds of interconnected vacuum tubes, the life of the individual tube takes on major importance. As previously noted several studies of this problem have been made. Below is given a brief summary of the effect of cathode temperature on tube life.

As discussed here, tube life is taken as the time during which the cathode emission and the transconductance remain within a fixed percent of normal. The following causes of tube failures are considered.

(1) Interface

(2) Poisoning

(3) Evaporation

Factors affecting these causes are:

(1) Cathode temperature

(2) Electrode temperature

(3) Bulb temperature

(4) Gas pressure within the envelope

These factors are affected by operating conditions such as[73]:

(1) Heater voltage

(2) Plate dissipation

(3) Screen dissipation

(4) Ambient temperature

(5) Altitude

(6) Vibration

(7) Control-grid impedance

In particular, an analysis of the relation between life and cathode temperature is part of the objective of this paper.

Appendix "A" gives the derivation of the relationship between the decay of apparent transconductance with interface formation, assuming that the single R-C network, stable with frequency, exists. This assumption will be valid to at least the first order. As shown by Van Der Ziel[61], an apparent transconductance is given by

$$g_m' = g_m/(1 + g_m Z_c)$$

where g_m is the original tube transconductance and Z_c is the interface impedance (also Child[11]). Eaglesfield[15] suggests that the cause of the short lives might be a negative feedback due to a growth of interface.

Decreasing the cathode temperature will effect some of the above causes so as to increase life and some so as to decrease life. The rate of formation of interface increases with the exponential of absolute temperature whereas the resistance increases with the reciprocal of temperature. Child[11] (Figures 3 and 4) has given curves substantiating the above theories. From this information it is concluded that, considering interface effects, life will increase with decreasing temperature.

It appears that poisoning of the cathode, and as a result loss of emission, will be proportional to some function of temperature. Poisoning is an effect which runs to completion during the early

tube history, however. Using Metson's[39] method an accurate determination of the gas integral characteristic can be made in a matter of a few hours and thus an evaluation of the effect of poisoning on life can be obtained. The proper interpretation of Metson's emission test as presented later may also give this information.

Evaporation, as previously discussed, will be virtually eliminated by any decrease of temperature.

The conclusions from the above facts are that the life of the tube will be benefically effected by reducing the cathode temperature. This has been substantiated by investigations made by the Bell Telephone Laboratories, Murray Hill (Figures 9 and 10, curtesy of Mr. J. O. McNally). Considering Figure 10, the plate current in each tube was approximately 8ma so that the current in one of the end positions of the string was 32 ma higher than that in the heater in the other end of the string. The results of life tests on several hundred tubes operated in the various positions are given in this figure and it shows the effect of higher-than-advantageous filament current. The average filament current was approximately 500ma. Wyman[73] and Koch[28], however, are of the opinion that the normal operating ranges of vacuum tubes are ideally chosen. It should be noted that Wyman's conclusions are based on the characteristics of rectifier tubes and that Koch was writing for R.C.A. tube manufacturing division on the use of existing tubes.

A side discussion of the variation of transmitting tube life with cathode temperature is given by Basnett[4]. His discussion of the

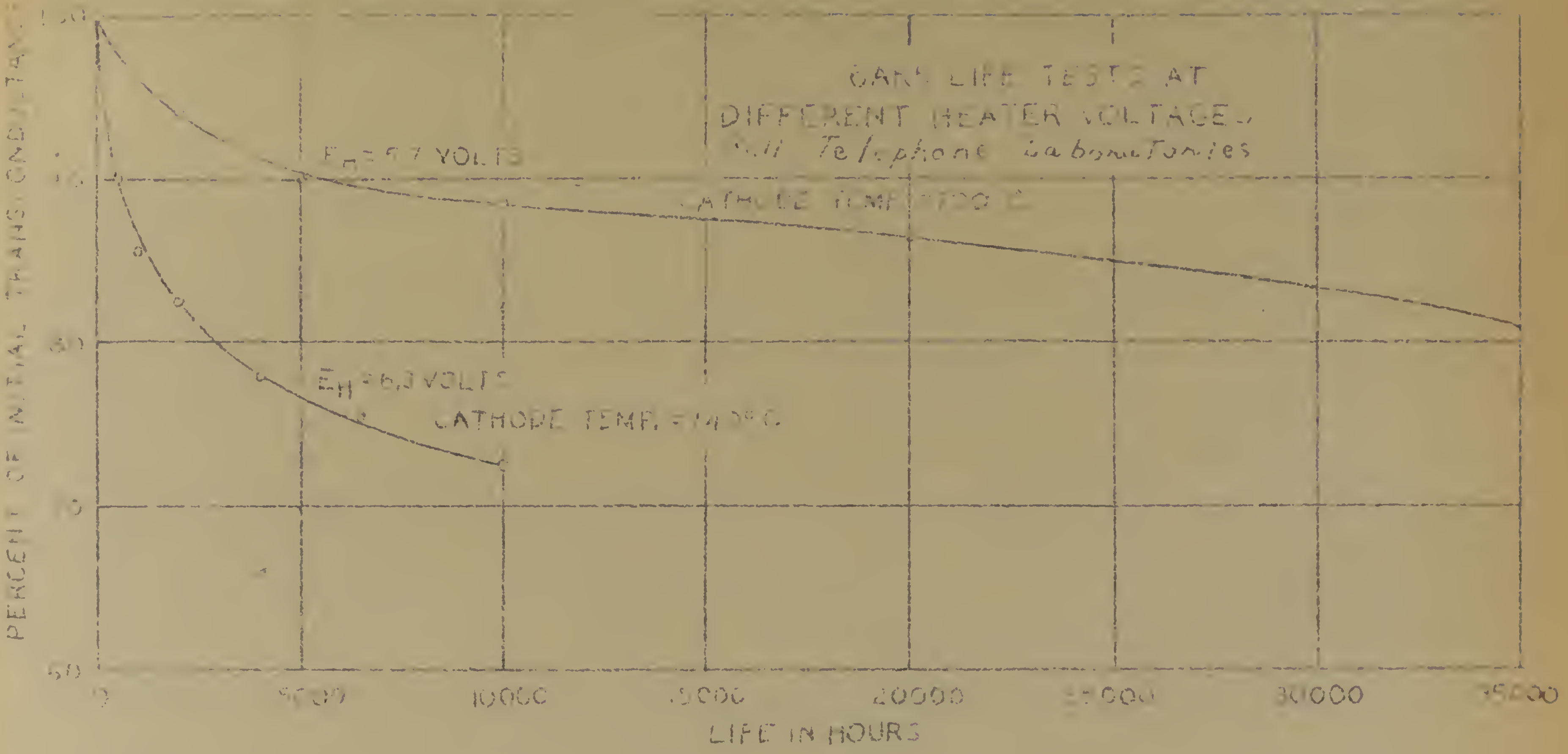
GAIN LIFE TESTS AT
DIFFERENT HEATER VOLTAGES
Bell Telephone Laboratories
E_H = 5.7 VOLTS
CATHODE TEMP. = 700°C
E_H = 6.3 VOLTS
CATHODE TEMP. = 740°C
PERCENT OF INITIAL TRANSCONDUCTANCE
100
90
80
70
60
0
5000
10000
15000
20000
25000
30000
35000
LIFE IN HOURS

Figure 9

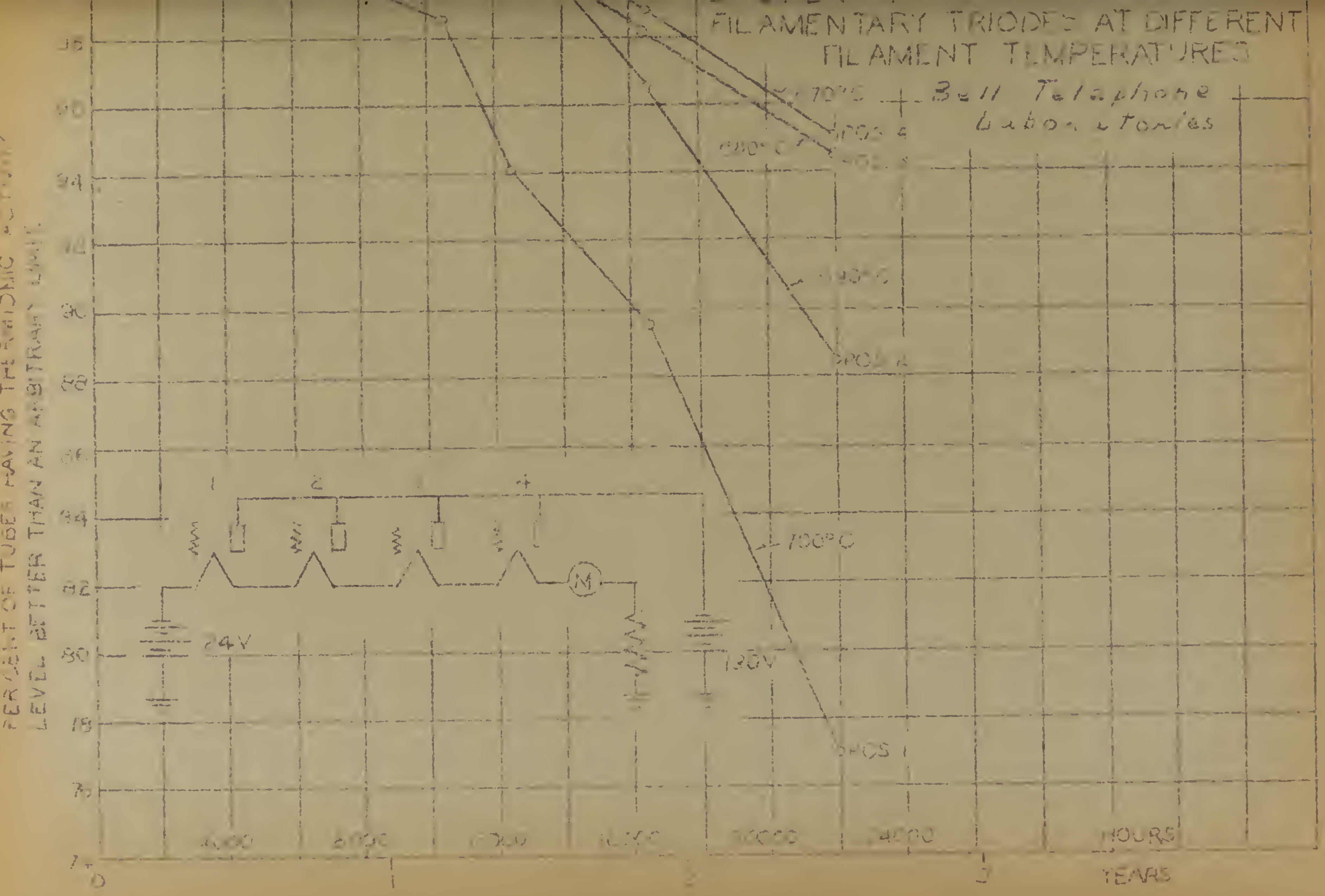

FILAMENTARY TRIODES AT DIFFERENT
FILAMENT TEMPERATURES
Bell Telephone
Laboratories
670°C
680°C
690°C
700°C
POS 4
POS 3
POS 2
POS 1
1
2
3
4
M
24V
130V
PER CENT OF TUBES HAVING THERMIONIC ACTIVITY
LEVEL BETTER THAN AN ARBITRARY LIMIT
98
96
94
92
90
88
86
84
82
80
78
76
74
4000
8000
12000
16000
20000
24000
HOURS
0
1
2
3
YEARS
AGE

Figure 10

beneficial effects of lower cathode temperatures as applied to tungsten cathodes will apply equally well to the filaments of indirectly heated tubes. Filament failure will drop proportionally to the lowering of the cathode temperature. Further information on the life characteristics are given by Herrmann[23], Redhead[50] and the Aeronautical Radio report[2].

In summary, it is definitely concluded that a great improvement in tube life can be expected by reducing the cathode temperature. The cathode temperature will, upon reduction, become somewhat critical, and consequently the filament heating power must be controlled. The temperature varies as the one-fourth power of the heater power[57], so the regulation of filament supply need not be as critical as initially might be expected. Another precaution to take is that the tube remain space charge limited. For most usages this would not present any problems.

CHAPTER IV

VARIATION OF TUBE CHARACTERISTICS WITH CATHODE TEMPERATURE

When variations of cathode temperature are considered, the effect on tube characteristics is at once of major concern. Investigations of the effect on tube characteristics of reducing filament voltage have been made by Winter[69], Benson[6,7] and the New York Naval Shipyard[46].

Winter reported that the effect of decreasing filament voltage on u, r_p and g_m for a 6C4 triode and a 6AG5 pentode is to increase u, increase r_p and decrease g_m (Figures 11, 12 and 13). The actual gain that may be achieved in a voltage amplifier increases. Increases in gain of 1.5 times were measured when the filament voltage was decreased from 6.3 to 3.0 volts, but in general the changes of characteristics were small. The Naval Shipyard report supports Winter's results. They indicated that there is a short time (10-20 minutes) downward drift of plate current for a reduced heater voltage, in particular for a voltage of 3.0 volts, before stability was reached.

Winter discusses the probable causes of these changes and attributes them to the physical movement of the virtual cathode toward the cathode as the temperature is decreased[13, 29, 51, 55].

Benson[6] discusses similar changes in characteristics, but concludes that the actual changes in u, r_p and g_m are minor and that

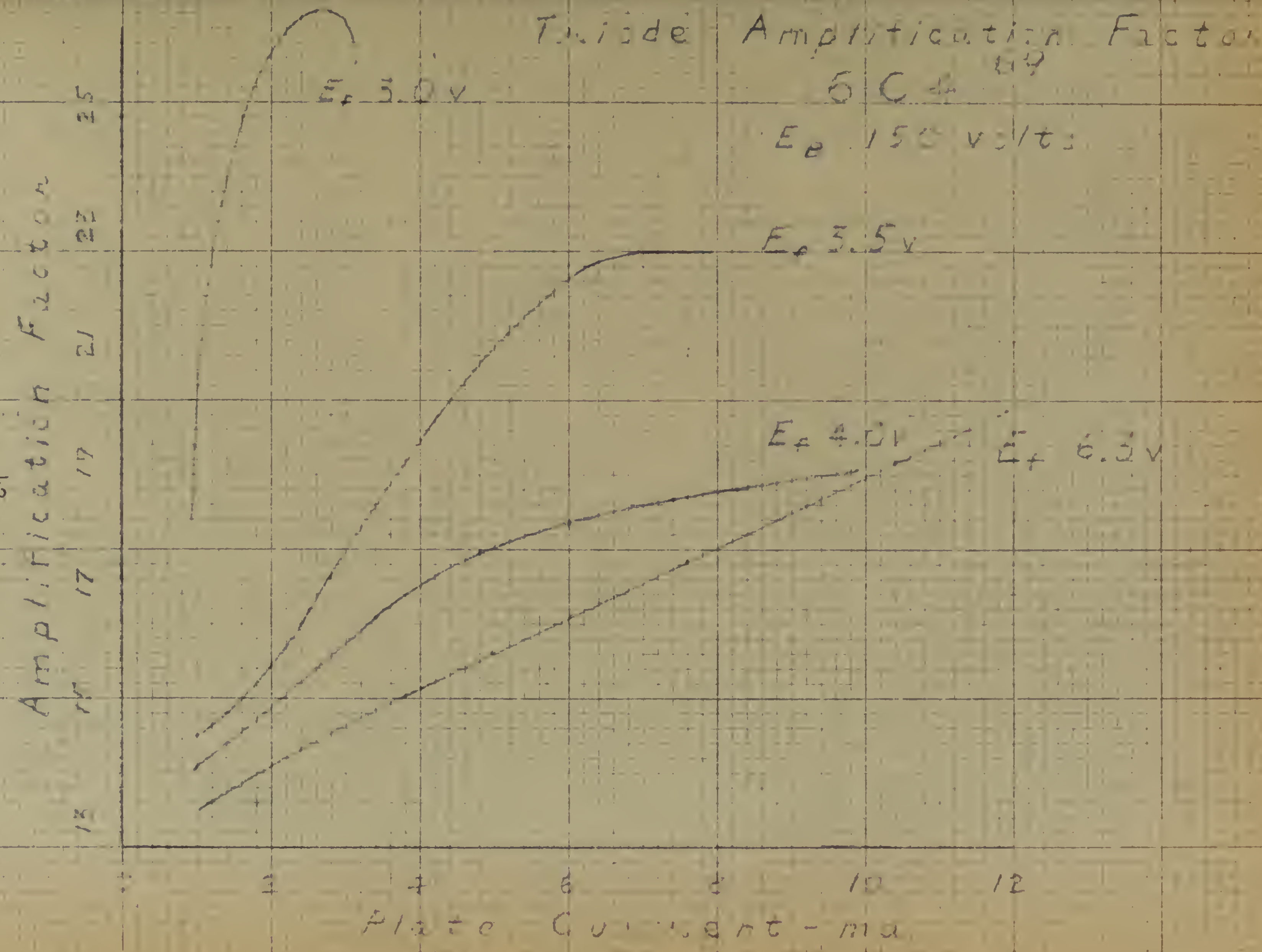

Triode Amplification Factor
6C4
Ep 150 volts
Ef 5.0 v
Ef 5.5 v
Ef 4.0 v
Ef 6.3 v
Amplification Factor
13
15
17
19
21
23
25
0
2
4
6
8
10
12
Plate Current - ma

Figure 11

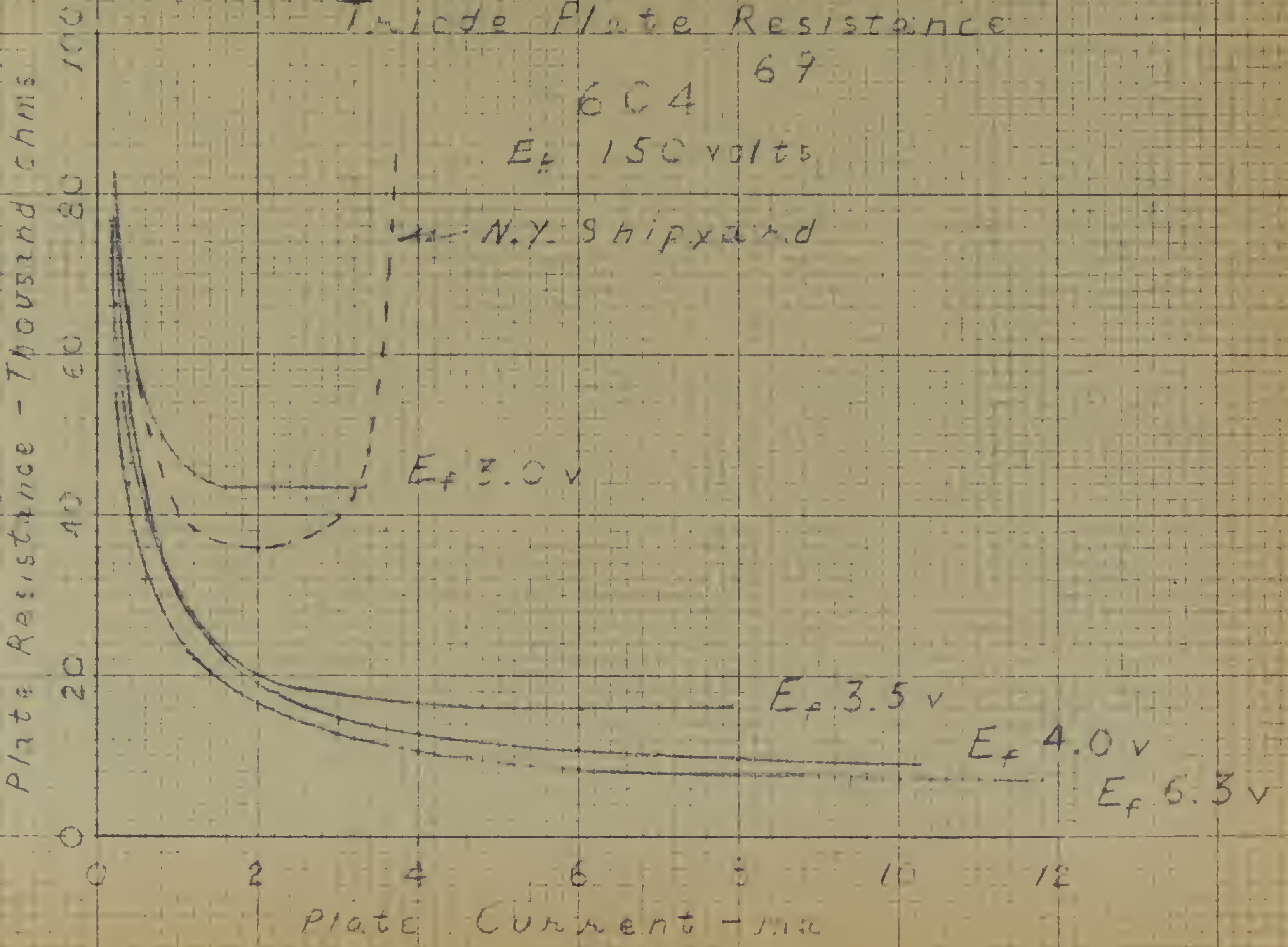

Triode Plate Resistance
67
6C4
E_b 150 volts
N.Y. Shipyard
E_f 3.0 v
E_f 3.5 v
E_f 4.0 v
E_f 6.3 v
Plate Resistance - Thousand ohms
0
20
40
60
80
100
Plate Current - ma
0
2
4
6
8
10
12

Figure 12

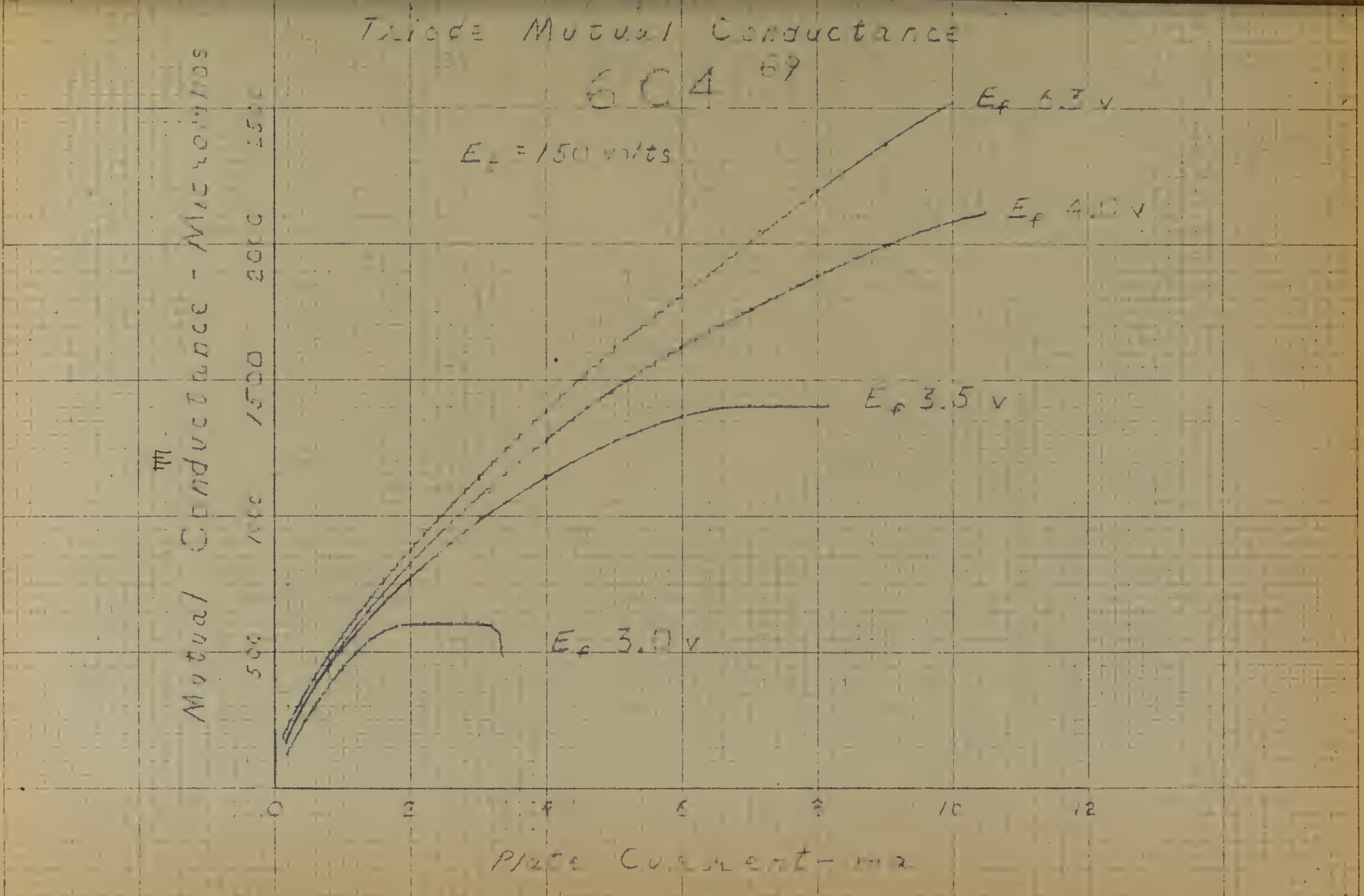

Triode Mutual Conductance
6C4
E_p = 150 volts
E_f 6.3 v
E_f 4.0 v
E_f 3.5 v
E_f 3.0 v
Mutual Conductance - Micromhos
500
1000
1500
2000
2500
Plate Current - ma
0
2
4
6
8
10
12

Figure 13

the real change occurs in a constant "c_2" which appears below.

$$i_p = g_m e_g + c_2 + e_p/r_p$$

This constant "c_2" is the vertical difference between two corresponding plate characteristic curves, one for standard voltage and the other for reduced filament voltage. The rate of change of "c_2" increases as filament voltage decreases. In any event, it is concluded that the effect of changing temperature can be interpreted as the addition of a voltage generator in the grid circuit.

Benson[7] gives an analytical analysis of five electronic voltage regulators considering the effect of this added generator, and concludes that its effect can be minimized by proper choice of the circuit.

CHAPTER V

TESTING PROCEDURES

As a result of the lack of general interest in the cathode temperature problem, testing procedures have not kept up with the general progress of electronic developments. Testing procedures can be placed into three divisions, (a) cathode temperature, (b) interface resistance and capacitance and (c) emission measurements.

Temperature measurement has classically been done by using special tubes with thermocouples embedded in the cathode, using tubes with windows cut through the anode so that the cathode can be viewed with an optical pyrometer, or by observing the emission limited current in a diode. For directly heated cathodes there exists a fourth method, that of taking resistance measurements of the cathode. This latter method may also be applied to indirectly heated cathodes, provided the empirical relation between heater resistance and cathode temperature is known.

When using the thermocouple, very thin wires (less than 0.1mm diameter) of platinum-rhodium provide the least influence on heat conduction and emission. It must be noted that the cathode temperature will vary along its surface, so several thermocouples or viewing windows must be used. The pyrometrical method has the advantage that it allows measurements of temperature without appreciable modification of the tube.

The retarded field method utilizes the fact that a plot of the

logarithm of the retarding field current I_r against voltage gives a straight line whose slope is determined only by the temperature of the cathode[5]. This temperature can then be calculated from the slope of the straight line using the formula[14, 23]

$$T = 5040\ dV_a/d\log I_r .$$

Until lately this equation could only be applied to diodes because of the potential field distortion caused by the grids of multi-element tubes. Ikehara[27] has developed a method whereby the theory of emission limited current can be applied to all tubes with apparently good accuracy (0.05%). He shows that with the grids at the potential of an undistorted plate-cathode field the initial plate current is a maximum. Expanding the expression for the initial current into a sine and cosine series and obtaining an expression for the fundamental and the n^{th} harmonic of a saturated current, he relates these to the absolute cathode temperature. The experimental procedure is to apply a very small 10KC signal to the grid and then by changing the retarding potential of the plate slightly until the third harmonic changes by 10 db relate this change to the absolute cathode temperature by the relationship

$$T_k = 10075\, \Delta E_{\text{(volts)}}.$$

It is this method that is used in this investigation for determining cathode temperatures. Once the temperature is determined for a particular value of heater power, other temperatures can be computed by the relationship

$$T_k \propto P^{\frac{1}{4}}\ \text{filament}[57] .$$

The measurement of interface components has taken two forms: (1) The computation of the resistance and time constant necessary to give the observed decay of plate current when a pulse is applied to the grid[16, 33], and (2) the observation of resulting changes of g_m because of interface resistance and capacitance[39, 61, 64]. With the proper precautions these two general methods will have comparable accuracy[45]. Appendix "A" gives the basic derivation of the relationship between g_m and interface resistance and capacitance which is used in these methods of measurement. The method of Eaglesfield[16] is used in this investigation.

Metson[39] gives a method of measuring emission. His method is one which produces relative information only. The measurement is made at very low cathode temperatures ($V_f = 2v$) in order to freeze the ions in their sites and therefore not reactivate the cathode during the measurement. A simple experiment has shown an increase in freedom of ionic or atomic movement by a factor of 10 as the filament voltage varies from 2 to 3 volts, and by a further factor of 40 for an increase in heater voltage from 3 to 4 volts.

CHAPTER VI

LABORATORY PROCEDURE

Six hundred hour aging tests were carried out along with tube characteristic checks for this investigation. Below is given the laboratory procedures followed. Worthy of special note are the satisfactory results of the method used in cathode temperature measurement.

1. Cathode Temperature Measurement

The method used in measuring cathode temperature was first described by Ikehara[27] in 1954. It is basically the specialized application of the saturation current law to multigrid tubes with refinements to reduce the various errors usually encountered.

In the case of diodes the following ratio of the m^{th} harmonic to the n^{th} harmonic of the initial saturated current is developed.

$$\frac{I_m}{I_n} = \frac{k_m \, J_m(jE_i/E_T)}{k_n \, J_n(jE_i/E_T)}$$

where J_m is the first m^{th} order Bessel's function

$k_n = 2/\sqrt{-1}$ n odd

$k_n = 2$ n even

E_i = small ac voltage applied to the inverse anode voltage

$E_T = T_k/11600$ volts

T_k = absolute temperature of the cathode

In the case of multi-electrode tubes the theory is developed that

when E_g is such that I_p becomes a maximum, the potential of the grid conductor is equal to that of the space, the field near the grid becomes uniform, and the electron paths are not disturbed. In this state the triode can be treated as a diode. Combining the above two developments the following relation is obtained.

$$T_k = \frac{100750\ (\Delta E)}{20 \log_{10} I'_n/I_n}$$

I'_n = n^{th} harmonic of the initial current when an added retarding plate voltage is applied

ΔE = the added retarding plate voltage

This reduces to

$$T_k = 10075\ (\Delta E)$$

when the ratio of I_n to I'_n becomes 10 db. Figure 14 shows the general circuit built for this investigation to determine cathode temperature. Figure 15 shows the circuit diagram of the amplifier used (available gain 112 db).

Tests were run to determine the accuracy of this method with the available equipment. One side of a 12AX7 twin triode was used with four values of heater voltage. The temperature was computed for each value and the log of the temperature plotted against the log of the filament power. A straight line plot resulted, but with a slope of 0.1685 rather than the theoretical 0.25. These temperatures were compared with those which would result in the proper slope and the percentage error computed. The average error was 2.82%. The results

Circuit Diagram for Measuring Cathode Temperature

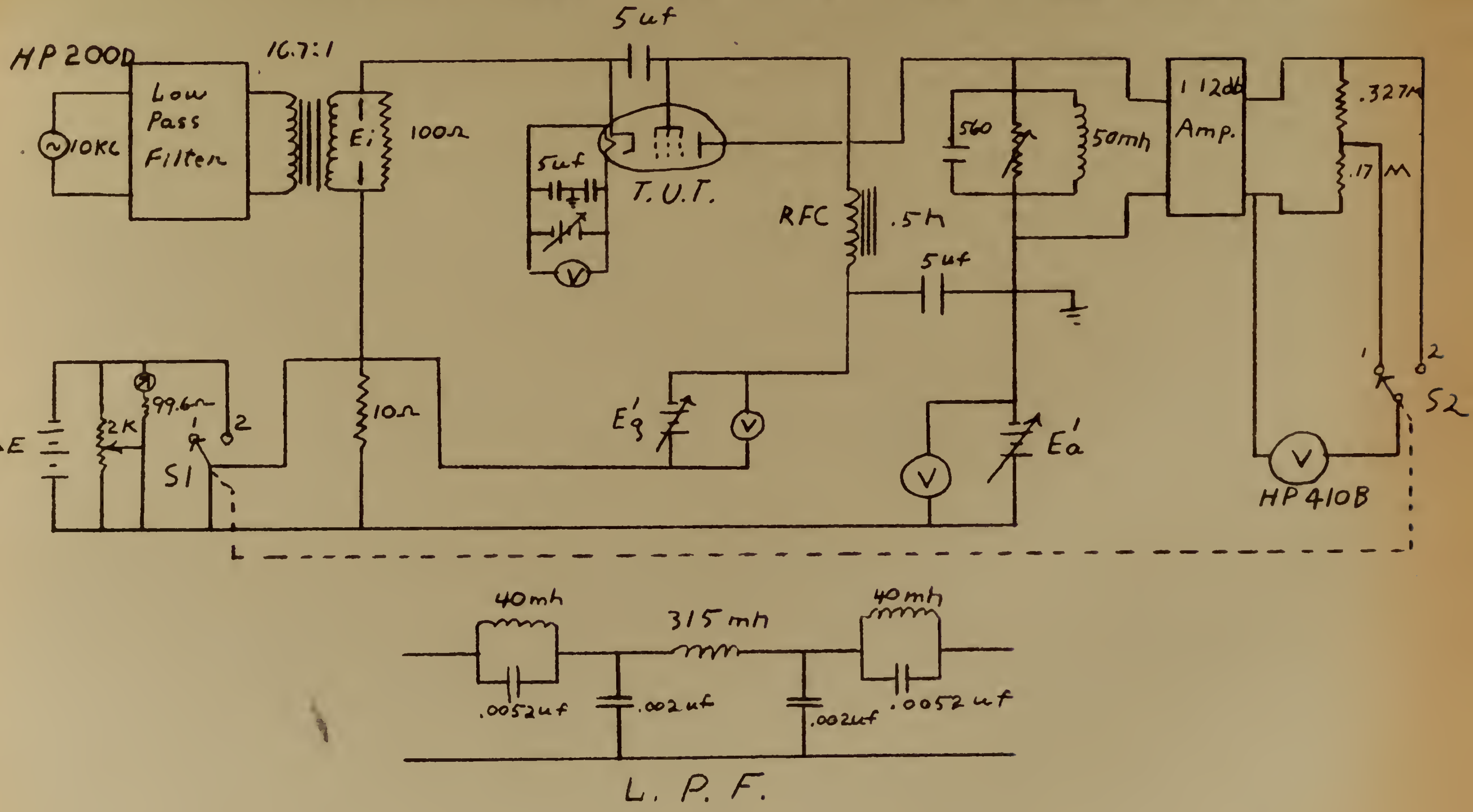


Figure 14

30 KC Amplifier

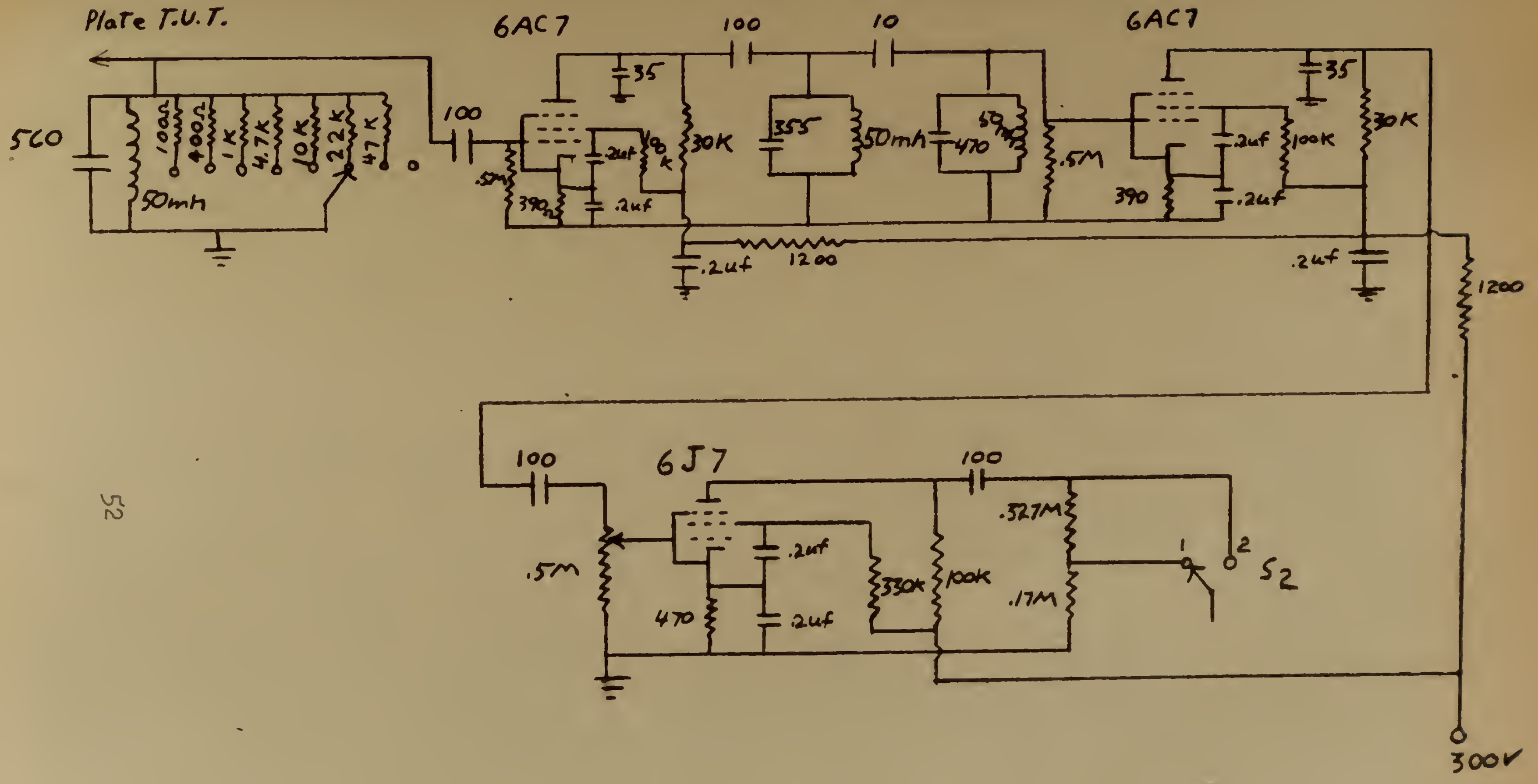


Figure 15

are given below.

E_f	I_f	P_f	T^oK 1/5.92	T^oK 1/4	%error
6.4	.149	.954	1128	1165	3.18
5.4	.132	.713	1058	1080	2.04
4.35	.118	.513	1027	995	3.22
3.6	.105	.378	946	920	2.83

For all of the temperature tests $E_i = 0.8$v at 10KC, $R_{tank} = 400$ ohms; the third harmonic, 30KC, was used through the amplifier. The procedure given by Ikehara was used and the general shape of all his curves was found to hold true.

2. Interface Measurement

The method of Eaglesfield[16] was used in this investigation to measure interface resistance and capacitance. A test filament voltage of 4v was used in order that the interface resistance be increased and its value be easier to determine.

As developed in Appendix "A",

$$\frac{V_o}{e_i} = \frac{g_m(R_o + Z_1)}{1 + g_m(R_o + R_3 + Z_1 + Z_2) + \frac{1}{r_p}(R_o + R_3 + Z_1 + Z_2)} .$$

Assuming that $u = 50$ and that $R_3 < R_o$, which is well taken for any activated cathode,

$$\frac{V_o}{e_i} = \frac{g_m(R_o + Z_1)}{1 + g_m(R_o + Z_1 + Z_2)} .$$

If R_o is adjusted so that $g_m R_o = 1$, then

$$\frac{V_o}{e_i} = \frac{1 + g_m Z_1}{2 + g_m(Z_1 + Z_2)} .$$

If the gain is then adjusted to be equal to $\frac{1}{2}$, then

$$Z_1 = Z_2.$$

The circuit used is given in Figure 16. The procedure is as follows.

(1) Choose three frequencies -- high, low and intermediate (5MC, 50KC, 500KC) and make the gain equal to $\frac{1}{2}$ at each frequency in turn.

(2) Set up the test tube and adjust the cathode current to a convenient value (1ma for 12AX7 and 3ma for 6BQ7A). Ensure that R_1 and C_1 are both zero.

(3) Place the switch in the "calibrate" position and adjust the oscillator so that the voltmeter reads 0.1v for each frequency in turn.

a. At 5MC, Z_1 and $Z_2 = 0$, therefore

$$\frac{V_o}{e_i} = \frac{g_m R_o}{1 + g_m R_o}$$

Adjust R_o so that $\frac{V_o}{e_i} = \frac{1}{2}$, $V_o = 0.05$v. Then $g_m R_o = 1$.

b. At 50KC, Z_1 and Z_2 equal R_1 and R_2 respectively. Adjust R_1 so that $\frac{V_o}{e_i} = \frac{1}{2}$, $V_o = 0.05$v. Then $R_1 = R_2$.

c. At 500KC, adjust C_1 so that $\frac{V_o}{e_i} = \frac{1}{2}$, $V_o = 0.05$v. Then $Z_1 = Z_2$ and therefore $C_1 = C_2$.

The readings thus obtained of R_1 and C_1 are equivalent to the interface resistance and capacitance respectively.

Interface Measurement

Circuit[16]

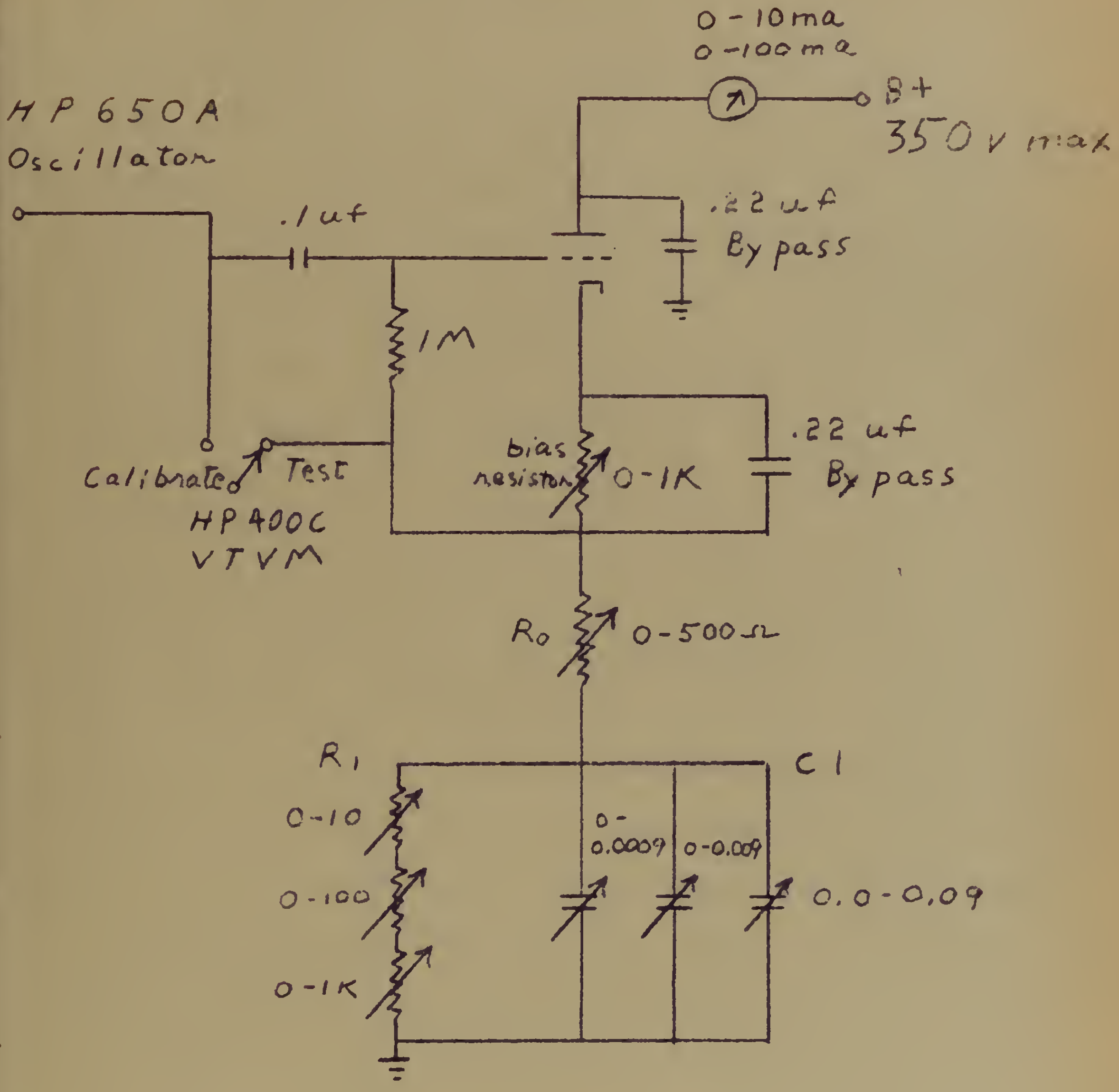


Figure 16

3. Characteristics Measurement

The tube characteristics were measured directly on the Hewlett-Packard laboratory vacuum tube testing bridge.

4. Emission Measurement

The emission characteristics of the test tubes were taken under the conditions described by Metson[39]. A filament voltage of initially 2.0 volts was used with the filament power being kept constant for succeeding measurements; the plate and cathode were grounded; the grid was at a +5v potential (Figure 17). The grid current was taken as being proportional to the saturated emission current.

5. Noise Measurement

Noise measurements were made using the tube in an amplifier circuit with a battery plate supply, grid at a dc bias but at ac ground and a varying dc filament supply (Figure 18). The amplified noise output was detected with an HP 400C voltmeter. In computing the equivalent grid noise resistance, the gain of the circuit for each value of filament voltage was measured, and then, knowing the load resistance (8.138 K), and the band width (650KC), the equivalent grid noise resistance was determined from the relation

$$\left(\frac{e_{out}}{A}\right)^2 = 4kT\,\Delta f\left(R_{grid} + \frac{R_L}{A^2}\right).$$

6. Aging

Thirty two tubes were used in the aging tests; sixteen each of

Emission Test

Circuit

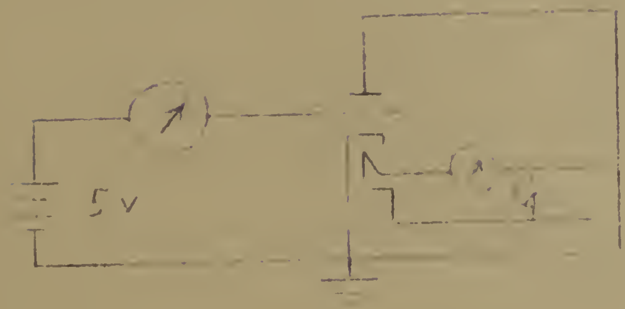


Figure 17

Noise Test

Circuit

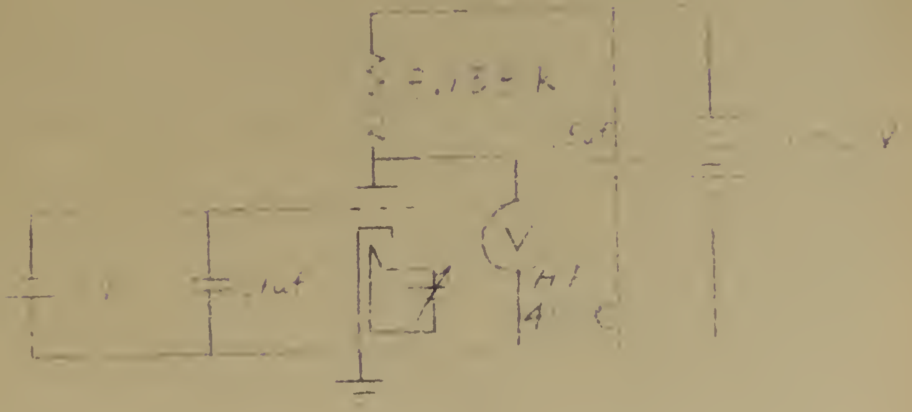


Figure 18

of 12AX7 and 6BQ7A twin triodes giving sixty-four test units. Tests were made on the tubes before aging, during aging and after the aging in accordance with Table I. The tube aging conditions are given in Table II. The 12AX7 tubes were Sylvania 448, B4T; the 6BQ7A tubes were R.C.A. 4-39. Figure 19 gives the aging circuit diagram. Low plate currents were used to accelerate interface formation. The aging filament voltages were arbitrarily chosen. The interface test filament voltage was chosen at four volts in order to increase the effective value of interface resistance and permit an early life indication of interface growth. Nergaard[45] has stated that the behavior of interface resistance with time during the first few thousands of hours does not give a clear indication of what will happen subsequently. This is contrary to the information of Child[11], whose results indicate that under certain conditions definite trends of resistance growth will develop during the first few hundred hours. An attempt to follow the results of Child is made in this investigation. In order to obtain the most accurate information on the emission capabilities of the cathode, the emission test was performed first in the series of tests, thus eliminating any possible activation of the cathode between the aging time and this test because of cathode current.

Table I

Tubes / Tests	A 12AX7 a	b	B 12AX7 a	b	C 6BQ7A a	b	D 6BQ7A a	b	E (not aged) 12AX7
Cathode Temp.	all	all	all	all	all	all	all	all	
g_m, r_p E_f 6.3	all	all	all	all	all	all	all	all	
* E_f test	all	all	all	all	all	all	all	all	
E_f range			1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4			1a, 2a, 3a, 4a
* E_c vs E_f	1,2,3,4		1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4			
I_f			1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4			
** Emission	all	all	all	all	all	all	all	all	
** Interface	all	all	all	all	all	all	all	all	
Noise									1a, 2a, 3a
Special									1a - g_m, r_p vs E_c for E_f = 6.3, 5.3, 4.3 E_b = 50, 100, 150

* Test repeated at 600 h

** Test repeated at 200, 300, 400, 500, 600 h

TABLE II

Tube Aging Conditions

Tube #	Ef volts	Cath. Temp. °K	Eb volts	Ec (-) volts	Ib ua	Tube #	Ef volts	Cath. Temp. °K	Eb volts	Ec (-) volts	Ib ua
A1a	4.2	870	23	0.5	.7	B1a	6.4	1073	19	0.9	1.0
A1b	4.25	854	24	0.5	.4	B1b	6.2	1083	19	0.9	.9
A2a	4.1	880	24	0.5	.55	B2a	6.3	1104	19	0.9	.9
A2b	4.4	880	23	0.5	.7	B2b	6.3	1107	19	0.9	1.0
A3a	4.2	882	24	0.5	.44	B3a	5.5	996	20	0.7	.7
A3b	4.3	887	23	0.5	.8	B3b	5.5	991	19	0.7	.9
A4a	4.2	870	23	0.5	.7	B4a	5.5	1014	19	0.8	1.0
A4b	4.25	850	24	0.5	.5	B4b	5.5	998	20	0.8	.8
A5a	5.1	978	21	0.6	1.3	B5a	6.3	1060	19	0.9	.9
A5b	5.2	982	23	0.6	.85	B5b	6.4	1065	19	0.9	1.0
A6a	5.1	962	24	0.8	.3	B6a	6.4	1077	18	0.9	1.1
A6b	5.15	984	19	0.8	1.64	B6b	6.3	1070	19	0.9	1.0
A7a	5.0	991	23	0.6	.8	B7a	5.7	960	19	0.8	.8
A7b	5.3	936	23	0.6	.6	B7b	5.8	1028	19	0.8	.9
A8a	5.1	1015	23	0.6	.74	B8a	5.75	1069	17	0.6	1.4
A8b	5.2	985	22	0.6	.9	B8b	5.75	1069	22	0.6	.1
C1a	4.1	887	5.7	0.7	.3	D1a	5.9	1048	27	1.3	.8
C1b	4.1	945	3.9	0.7	.7	D1b	5.9	1048	23	1.3	1.9
C2a	4.1	878	5.0	0.6	.4	D2a	5.9	1030	27	1.3	1.0
C2b	4.1	878	5.9	0.6	.3	D2b	5.9	1040	24	1.3	1.6
C3a	3.9	885	5.9	0.5	.3	D3a	5.9	1110	22	1.8	1.9
C3b	3.9	854	5.2	0.5	.46	D3b	5.9	1010	25	1.8	1.3
C4a	3.9	950	4.8	0.6	.54	D4a	5.9	1090	20	1.8	2.5
C4b	3.9	902	6.0	0.6	.2	D4b	5.9	1011	27	1.8	.6
C5a	4.9	990	5.6	0.7	.3	D5a	6.4	1042	26	1.8	1.1
C5b	4.9	1009	4.6	0.7	.56	D5b	6.4	1111	21	1.8	2.3
C6a	4.9	1007	6.1	0.7	.2	D6a	6.4	1123	19	1.8	2.8
C6b	4.9	968	4.7	0.7	.54	D6b	---	----	--	---	---
C7a	4.9	955	6.0	0.8	.2	D7a	6.4	1242	26	5.3	.1
C7b	4.9	964	3.2	0.8	.9	D7b	6.4	1123	23	5.3	.9
C8a	4.9	993	5.2	0.8	.4	D8a	6.4	1166	22	1.8	2.1
C8b	4.9	993	4.0	0.8	.7	D8b	6.4	1126	21	1.8	2.2

Note: D6b failed during test because of disconnected pin.

TABLE II

continued

Summary

Tube	Cathode Temperature °K
12AX7	
A1a, A1b, A2a, A2b, A3a, A3b, A4a, A4b.	850-880
A5a, A5b, A6a, A6b, A7a, A7b, A8b, B3a, B3b, B4b, B7a.	936-998
A8a, B1a, B1b, B2a, B2b, B4a, B5a, B5b, B6a, B6b, B7b, B8a, B8b.	1014-1107
6BQ7A	
C1a, C1b, C2a, C2b; C3a, C3b, C4a, C4b.	854-902
C5a, C6b, C7b, C8a, C8b, C7a.	955-993
C5b, C6a, D1a, D1b, D2a, D2b, D3b, D4a, D4b, D5a.	1007-1048
D3a, D5b, D6a, D7a, D7b, D8a, D8b.	1110-1242

Tube [illegible] Circuit

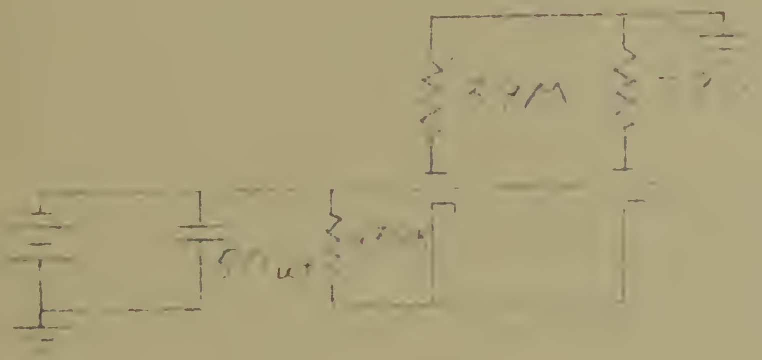


Figure 19

CHAPTER VII

EXPERIMENTAL RESULTS

The following results were obtained by the writer during the U. S. Naval Postgraduate School Industrial Tour from 3 January to 18 March, 1955, at the Hewlett-Packard Company, Palo Alto, California. The objectives of this laboratory work were to obtain experimental data in support of the ideas presented in Chapter I.

1. Interface

Figure 20 gives the results of the interface resistance measurements. The measurements of interface capacitance were erratic and inconclusive. The "A", "B", "C" and "D" nomenclature refers to Table II. It is to be noted that, as expected, the value of interface resistance did increase with aging temperature. The extra curve for the 6BQ7A tubes aged at 1110-1242°K was given to emphasize this point. Tables IIIA and IIIB give the hour by hour results. It is to be noted here that while the absolute values of relative resistances varied, the general shapes of the plots of resistance with time are very much the same in corresponding temperature ranges. From these values it appears that the cathode temperature of tube A8a was incorrectly determined. In order to emphasize the variation of resistance with temperature and to reduce the effect of errors of temperature measurement, the plots were given for the major temperature groups only.

At the 200 hour test the value of interface resistance measured was in the order of 260 ohms. The value of interface capacitance was

Interface Resistance Growth

for different cathode temperatures

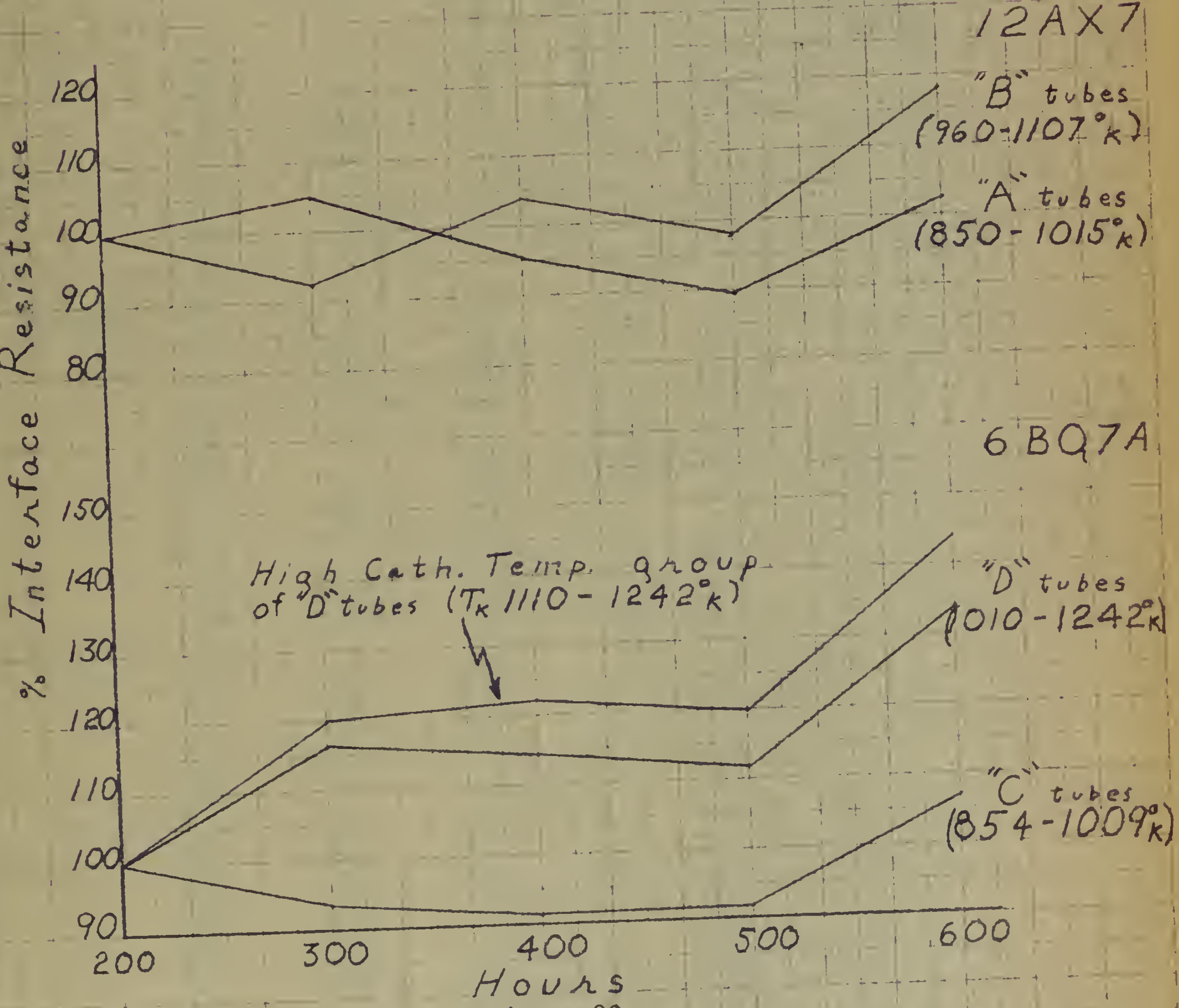


Figure 20

TABLE IIIA

Individual Interface Resistance Results in Percent (200h = 100%)

12AX7

Temp. °K	#	Interface Resistance % 300h	 400h	 500h	 600h
850-880	A1a	107	96.4	82.3	89.3
	A1b	111	100	77	107.7
	A2a	96.4	92.7	88.8	95.4
	A2b	107	100	92	107
	A3a	103.7	96.3	92.7	103.7
	A3b	103.7	92.7	85.6	100
	A4a	107.5	96.2	96.2	107
	A4b	111.5	100	92.2	103.9
936-998	A5a	100	89.3	89.3	100
	A5b	107.7	96.2	88.5	103.8
	A6a	100	92.7	85.8	96.5
	A6b	103.6	96.2	92.6	107.3
	A7a	103.8	100	92.3	107.6
	A7b	100	85.7	89.3	100
	A8b	111.9	100	96	107.9
	B3a	98.4	100.4	92.4	116
	B3b	92.4	106.2	96.2	120
	B4b	96	101.5	101.5	122
	B7a	92.3	94.6	93.9	119.3
1014-1107	A8a	103.6	92.6	88.8	100
	B1a	---	116	98.5	112.4
	B1b	100	112	109.2	120
	B2a	81.5	97.4	90.8	115.6
	B2b	100	107.1	105.9	114.3
	B4a	96	105.1	97.1	122.2
	B5a	100	108.7	97.5	126.6
	B5b	92.3	100	93.8	115.2
	B6a	92.3	93.5	96.3	120
	B6b	88.5	101.1	100	113.2
	B7b	88.5	101.8	95	112.6
	B8a	88.5	101.8	96.3	119.3
	B8b	95.8	112.3	106.2	126.2

TABLE IIIB

Individual Interface Resistance Results in Percent (200h = 100%)

6BQ7A

Temp. °K	#	Interface Resistance % 300h	400h	500h	600h
854-902	C1a	100.4	95.4	100.4	126.5
	C1b	91	92	90.5	100.4
	C2a	87.3	86.8	84.8	104
	C2b	85.5	83.5	81	102
	C3a	93.3	93.3	97	104
	C3b	95	94	93.3	103.4
	C4a	93.2	91	92.6	104.2
	C4b	91	89	89	103.5
955-993	C5a	95.6	89	95.6	112.3
	C6b	83.8	79.9	81.4	98.7
	C7b	88.8	88.2	88.8	107.8
	C8a	96.5	94.1	101.5	106
	C8b	95	92	97.5	105.4
	C7a	93.8	91.6	96.3	105.2
1007-1048	C5b	106.6	109.5	104.8	120
	C6a	90.2	91.8	88.7	109.6
	D1a	115	98.2	104.2	117.4
	D1b	103.4	105.8	98.8	119.2
	D2a	119.3	109.8	111.6	124.6
	D2b	110.9	107.3	104.8	123.5
	D3b	111.1	108	104.9	130.2
	D4a	125.2	112.3	118.1	129
	D4b	107.2	107.2	101.3	125
	D5a	119.3	109.3	109.3	128
1110-1242	D3a	116.4	107.5	110.7	129
	D5b	100	108.7	101.6	131.3
	D6a	146	144.3	147.5	166.5
	D7a	124.2	133	119.2	135.5
	D7b	122.6	126	130.4	150.4
	D8a	119.6	124.1	121.8	153.5
	D8b	115.6	111.2	101.8	137.1

in the order of 400 uuf. The tubes used during the test were new tubes drawn from the commercial stock of the manufacturers previously indicated. It must be remembered that in order to have operational meaning the values of interface resistance and capacitance should be measured with the tube under the exact operating conditions at which it is to be used. In this case, since only relative values were important, it was necessary only to insure that the test conditions and aging conditions were the same.

2. Emission

Figure 21 gives the plots of the emission measurement results. The maximum emission measured was taken as 100%. Table IV gives the starting and 600 hour values of the average emission currents and the range of values obtained as percentages of the average for the various temperature ranges.

The emission tests were made using a Weston Model 785 Industrial Circuit Tester to indicate filament current, an HP Model 420 Milliampere Meter for values above 100ua and a Westinghouse 100ua full scale microammeter for values below 100ua to indicate grid current and an HP Model 410B VTVM to indicate filament voltage. The value of filament current was read to within 0.001a, grid current below 100ua to within 0.5ua and above 100ua to within 5ua, and filament voltage to within 0.01v. Because the filament power was necessarily kept constant for all of these readings, the meters were reset for each reading. The accuracy of these measurements must be considered

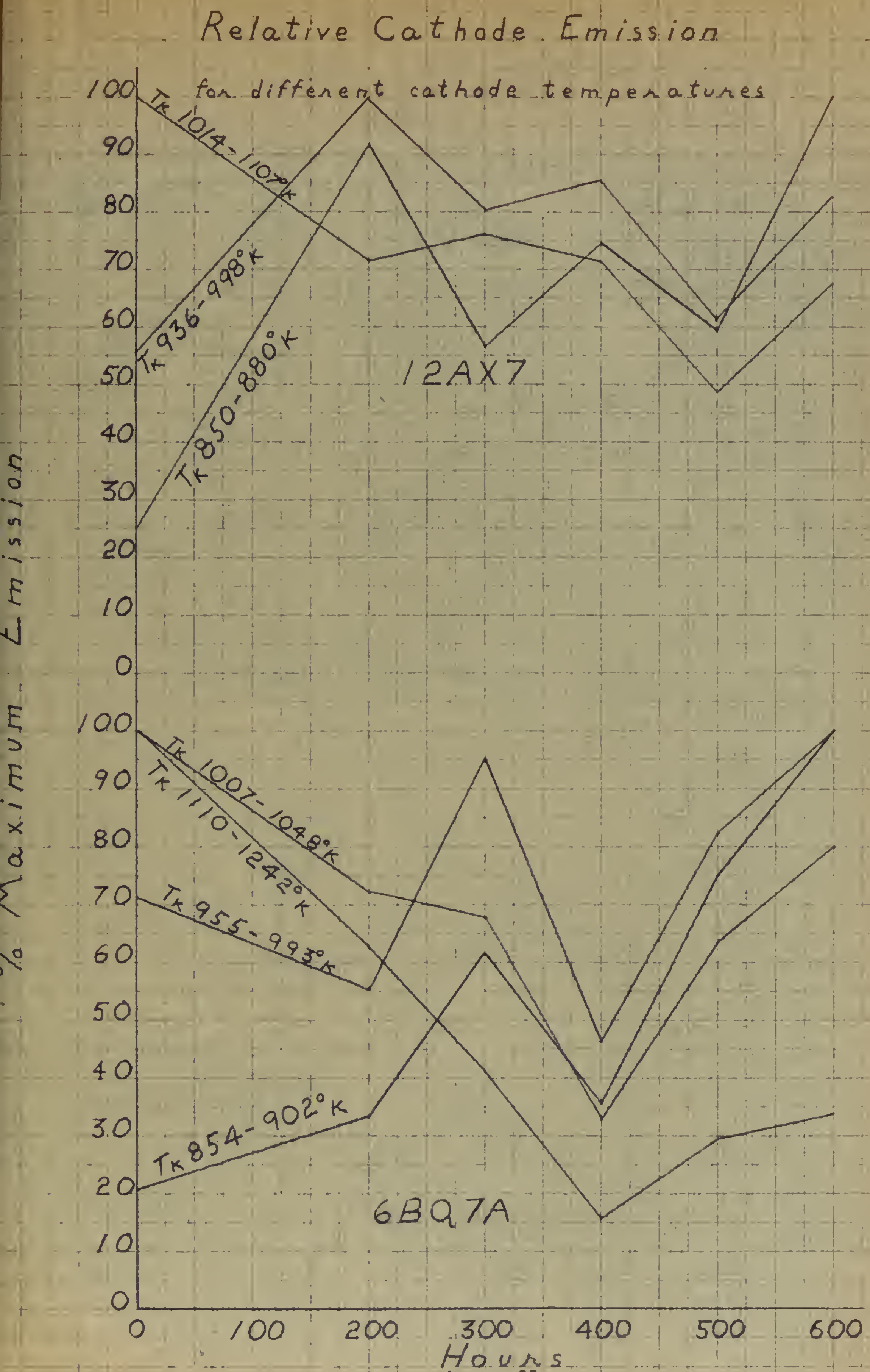

Relative Cathode Emission
for different cathode temperatures
% Maximum Emission
Hours
0
100
200
300
400
500
600
100
90
80
70
60
50
40
30
20
10
0
12AX7
Tk 1014-1107°K
Tk 936-998°K
Tk 850-880°K
6BQ7A
Tk 1007-1048°K
Tk 1110-1242°K
Tk 955-993°K
Tk 854-902°K

Figure 21

TABLE IV

Summary of Relative Emission Measurements

Tube Type	Temp. °K	Start Ave. ua	Start Range % of ave.	600h Ave. ua	600h Range % of ave.	% tubes where final value of emission was higher than initial value
12AX7	850-880	52.2	23-203	206.2	21-216	100
	936-998	93.6	45-160	139.2	83-134	73
	1014-1107	147.6	32-203	99.4	28-212	30
6BQ7A	854-902	195.0	27-241	958.0	35-162	100
	955-993	286.0	15-244	402.0	37-214	100
	1007-1048	234.0	2.6-325	187.0	5.4-219	50
	1110-1242	271.0	30-207	91.0	20-253	0

to be rather low due to the measuring equipment used. However, because of the continual resetting of filament power and the fact that all of the tubes of the given range and at a particular time had the same relative emission changes, it is believed that these curves do represent a fair indication of the emission behavior. Other tests, where high plate currents at low cathode temperatures were attempted before and then after aging, also indicated an improvement in the activation of the "C" tubes. Worthy of note here is (a) the general increase of emission with age and decreasing cathode aging temperature and (b) the tremendous range of emission currents measured, 2.6 to 325 percent in one temperature range. It must be remembered that the values of emission measured here are much less than would be available at normal cathode temperatures. The attempt here is to obtain a relative saturated emission indication in order to perhaps obtain an idea as to the activation of the cathode and the possibility of cathode poisoning.

3. Noise

Noise measurements were made in a screen room as described above on three tubes. The individual results are given in Figure 22.

4. Tube Characteristics

The accuracy of the tube characteristic measurements is considered to be within 5%. Variations of tube characteristics with grid voltage for different filament and plate voltages are given in Figures 23, 24 and 25. These are typical curves for a 12AX7 tube. These curves

Percent Variation of Noise Resistance with Filament Voltage

12 AX7

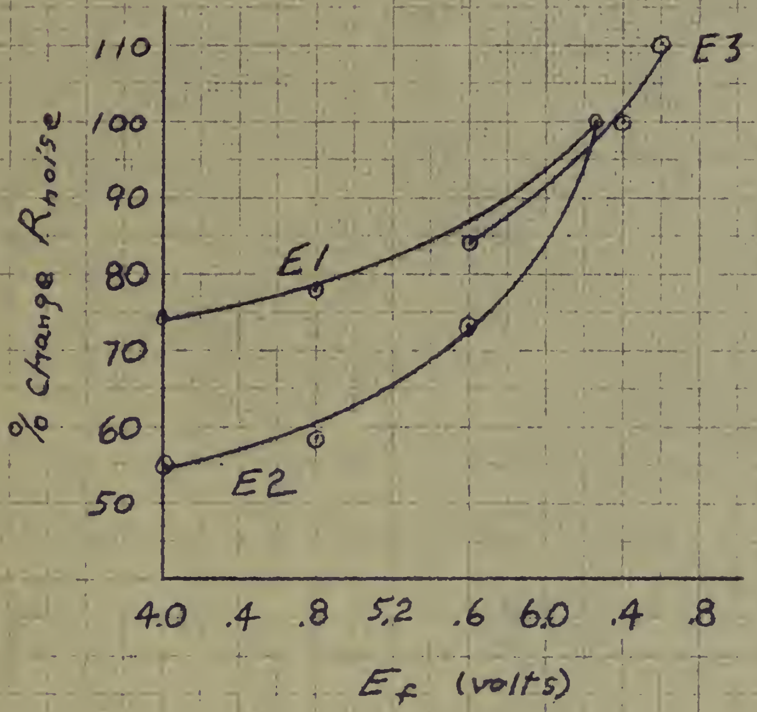


Figure 22

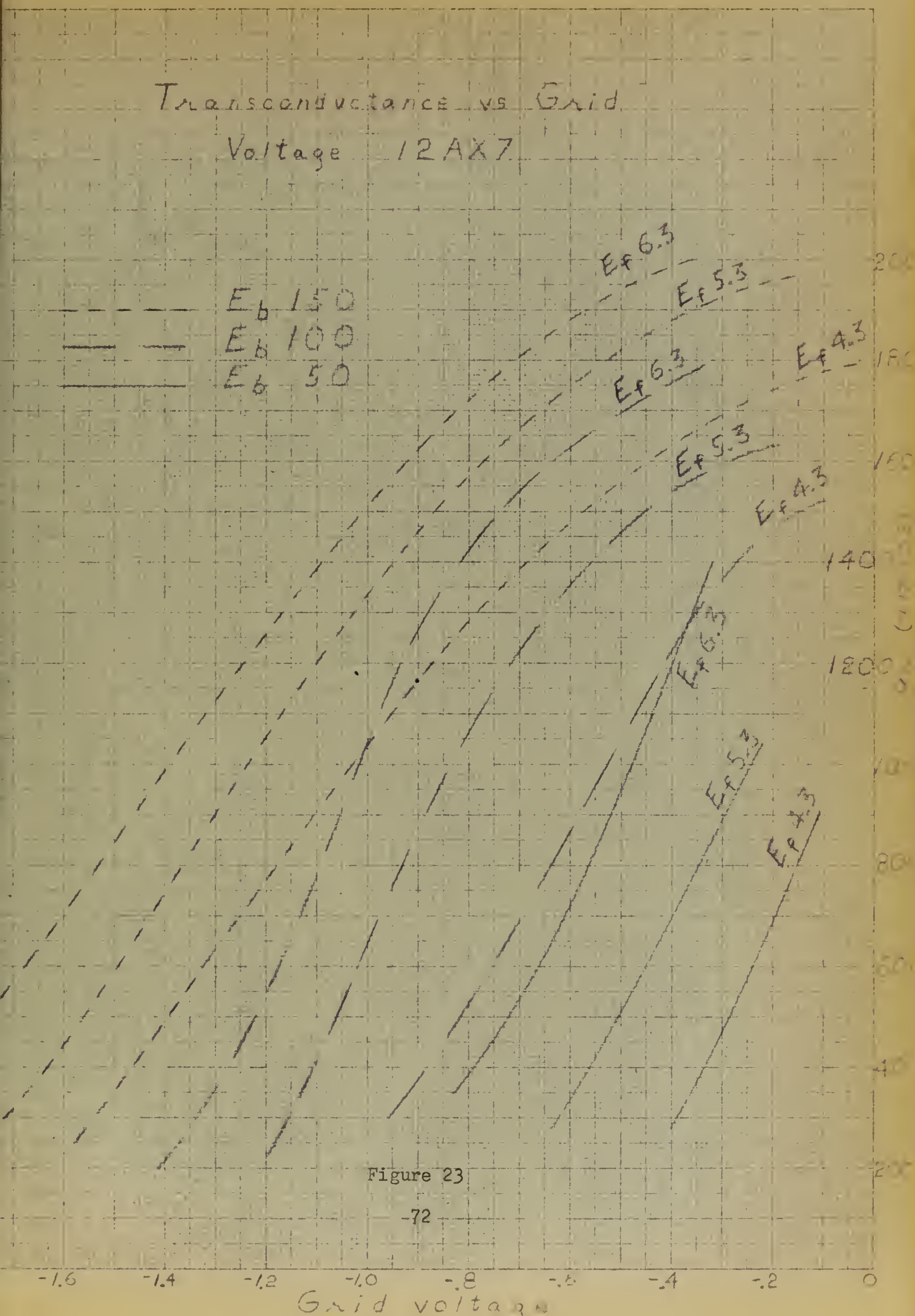

Transconductance vs Grid
Voltage 12AX7
E_b 150
E_b 100
E_b 50
Ef 6.3
Ef 5.3
Ef 4.3
Ef 6.3
Ef 5.3
Ef 4.3
Ef 6.3
Ef 5.3
Ef 4.3
200
180
160
140
1200
100
80
60
40
20
-1.6
-1.4
-1.2
-1.0
-.8
-.6
-.4
-.2
0
Grid volta

Figure 23

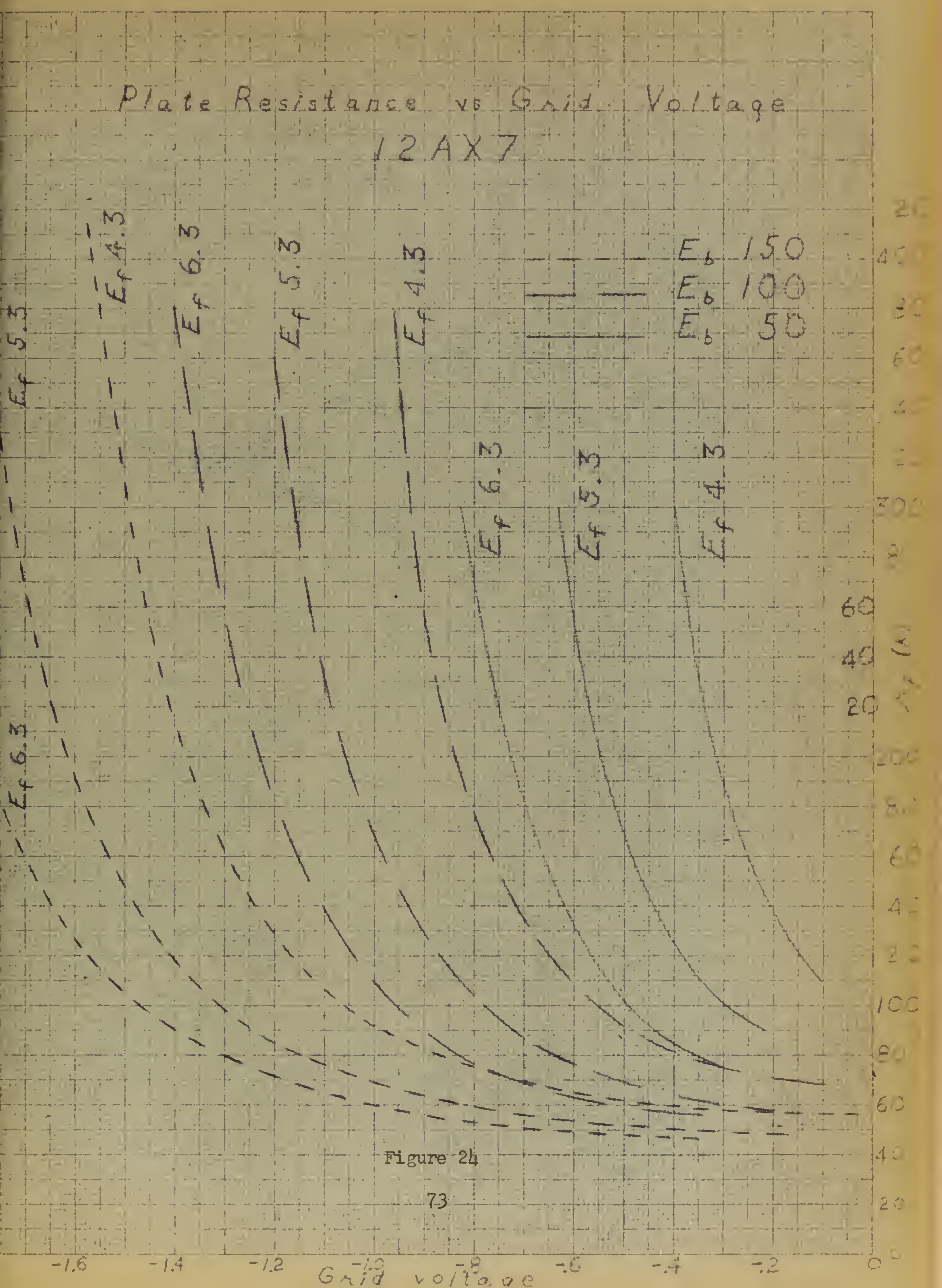


Plate Resistance vs Grid Voltage
12AX7
Eb 150
Eb 100
Eb 50
Ef 5.3
Ef 4.3
Ef 6.3
Ef 5.3
Ef 4.3
Ef 6.3
Ef 5.3
Ef 4.3
Ef 6.3
60
40
20
100
60
40
20
0
-1.6
-1.4
-1.2
-1.0
-.8
-.6
-.4
-.2
Grid voltage

Figure 24

should be combined with Figures 11, 12 and 13 to give a complete description of the variation of tube characteristics with filament voltage. Figure 26 gives the results of plate characteristics measurements on four tubes before and after the aging. These tubes were aged at 936-998°K. The average and the ranges of values are indicated for one grid voltage and two different filament voltages.

Figures 27, 28, 29, 30 and 31 form a family of curves giving the "before" and "after" aging values of grid voltage with changes of filament voltage for different plate currents and different aging temperatures. These represent average values of the following numbers of test units.

12AX7	850-880°K	4 units
	936-998°K	3 units
	1014-1107°K	5 units
6BQ7A	854-902°K	8 units

All of the tubes checked above gave curves of the same general shape. Their vertical positions varied as much as 10%. Figure 32 gives a typical plot of grid voltage against both filament voltage and cathode temperature for one tube. It is to be noted that a relatively linear relationship exists between the grid voltage and the cathode temperature. The average slope obtained with four tubes, computed for the indicated values of plate current, was 2.875 X 10^{-3} volts per degree absolute.

Figures 33, 34 and 35 give the variations of characteristics with filament voltage for different combinations of plate voltage and currents. These curves represent averages of four units.

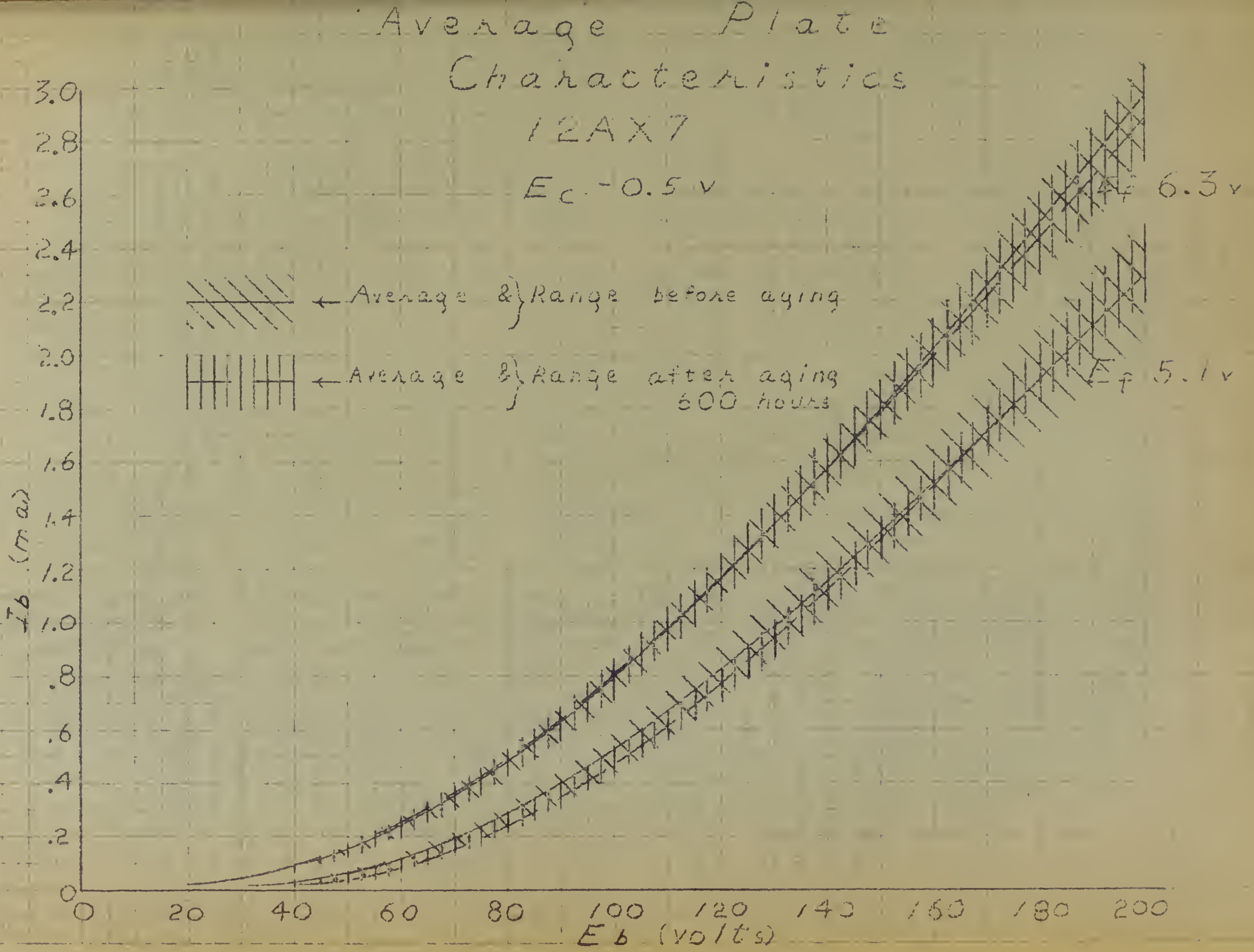

Average Plate Characteristics
12AX7
Ec -0.5 v
← Average & Range before aging
← Average & Range after aging 600 hours
Ef 6.3 v
Ef 5.1 v
Ib (ma)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
20
40
60
80
100
120
140
160
180
200
Eb (volts)

Figure 26

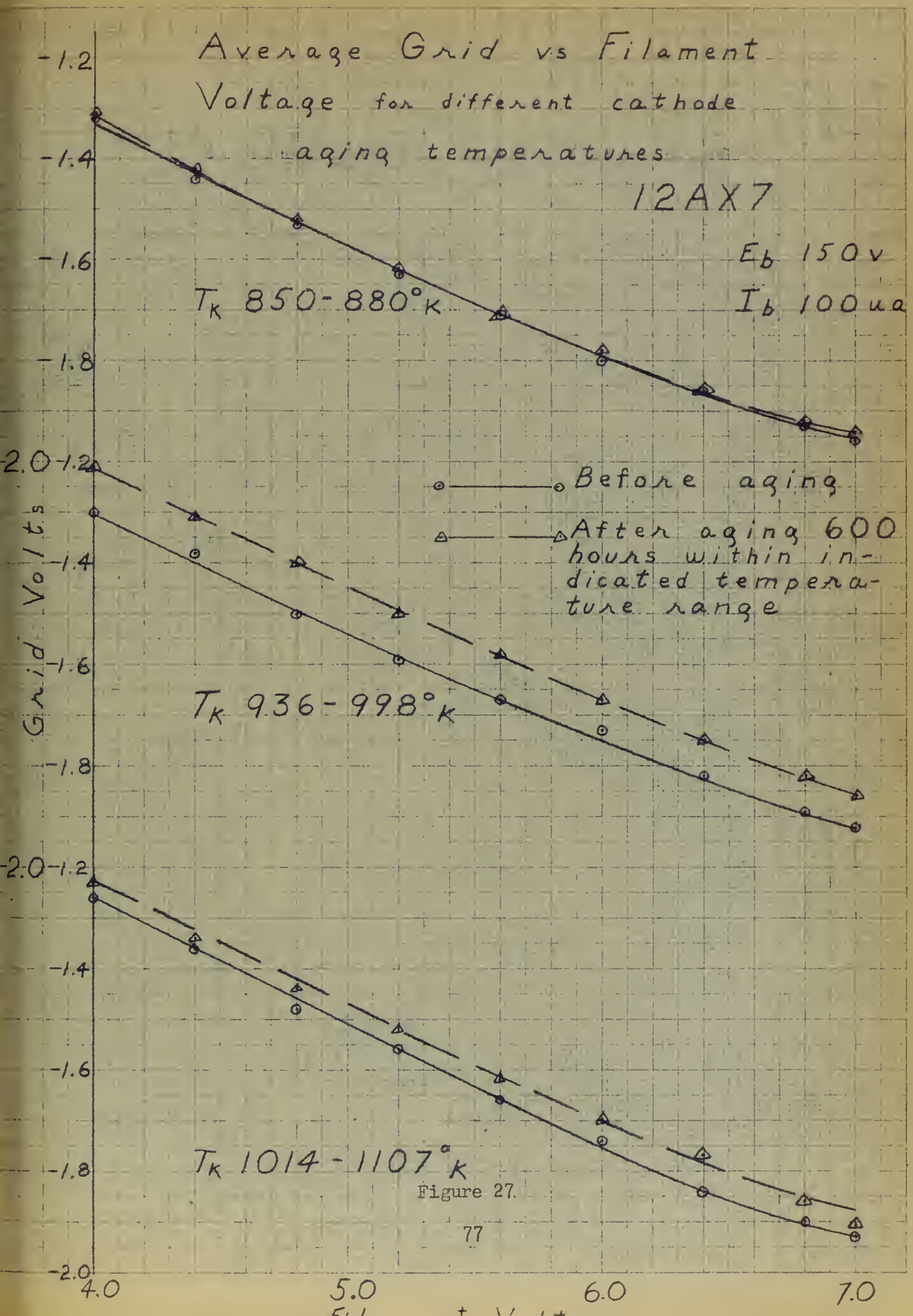

Average Grid vs Filament Voltage for different cathode aging temperatures
12AX7
Eb 150v
Ib 100ua
Tk 850-880°k
Tk 936-998°k
Tk 1014-1107°k
Before aging
After aging 600 hours within indicated temperature range
Grid Volts
-1.2
-1.4
-1.6
-1.8
-2.0-1.2
-1.4
-1.6
-1.8
-2.0-1.2
-1.4
-1.6
-1.8
-2.0
4.0
5.0
6.0
7.0

Figure 27.

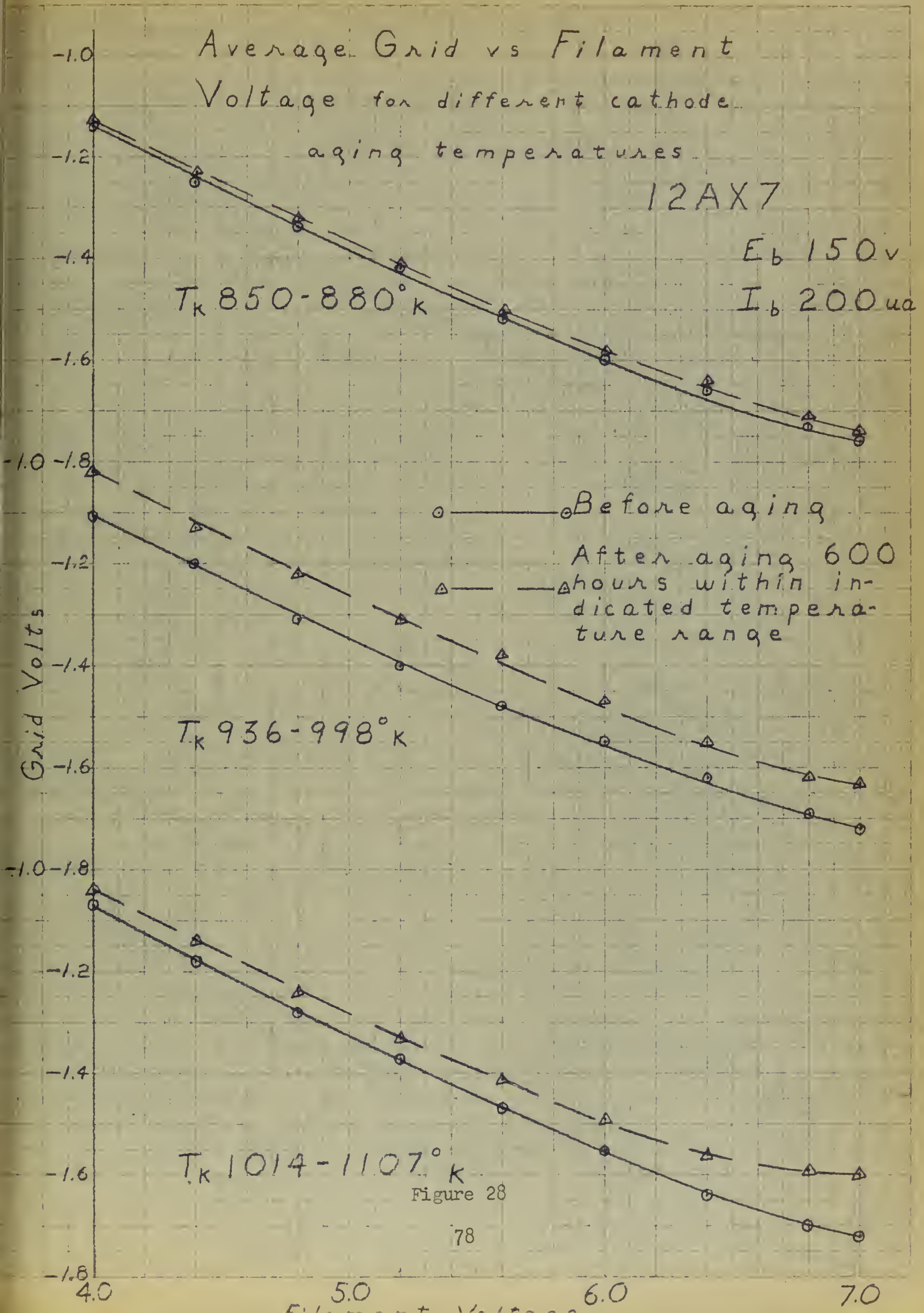

Average Grid vs Filament Voltage for different cathode aging temperatures
12AX7
Eb 150v
Ib 200ua
Tk 850-880°K
Tk 936-998°K
Tk 1014-1107°K
Before aging
After aging 600 hours within indicated temperature range
Grid Volts
-1.0
-1.2
-1.4
-1.6
-1.0 -1.8
-1.2
-1.4
-1.6
-1.0 -1.8
-1.2
-1.4
-1.6
-1.8
4.0
5.0
6.0
7.0

Figure 28

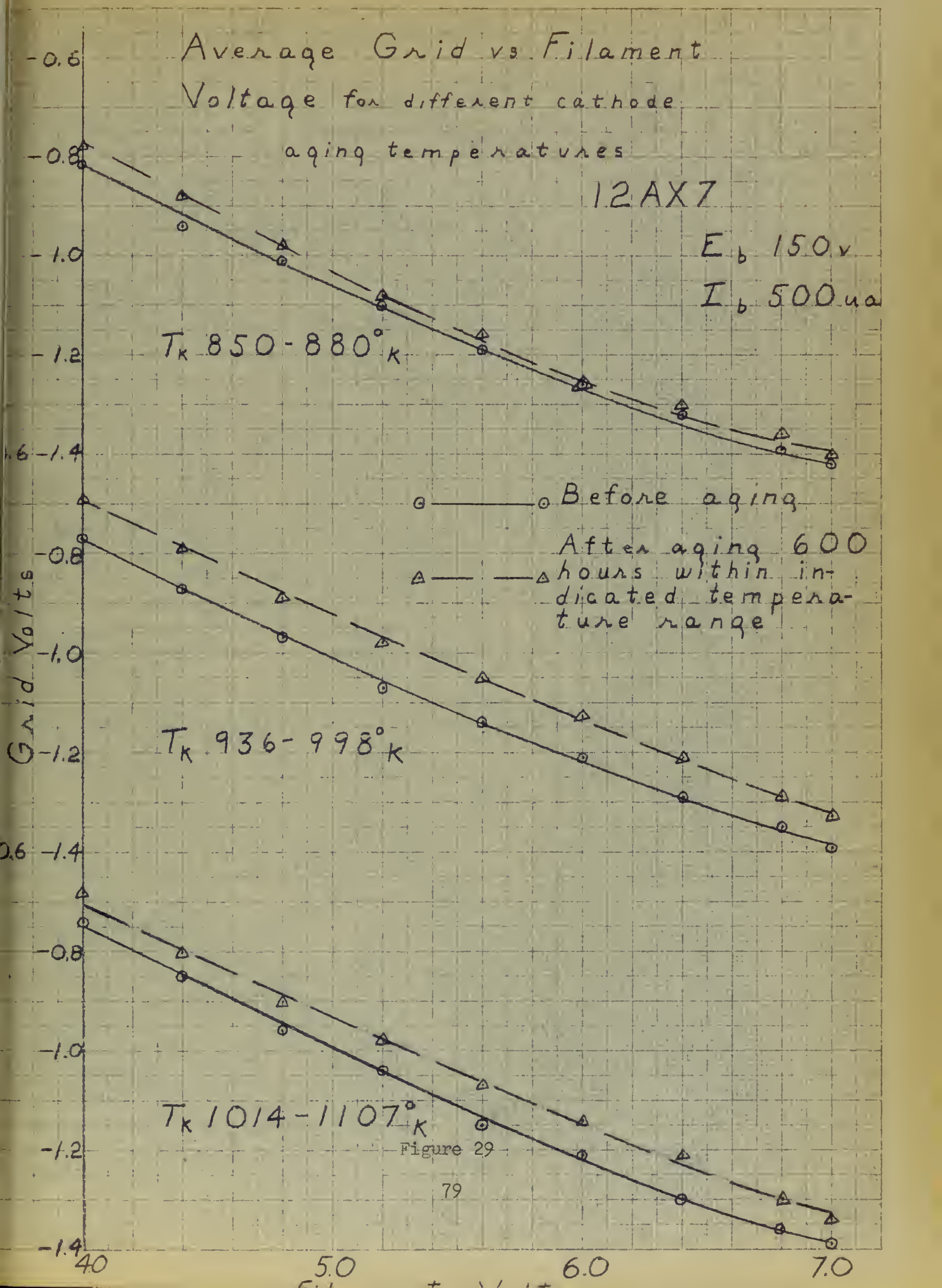

Average Grid vs Filament Voltage for different cathode aging temperatures
12AX7
E_b 150 v
I_b 500 ua
T_K 850-880° K
T_K 936-998° K
T_K 1014-1107° K
Before aging
After aging 600 hours within indicated temperature range
Grid Volts
-0.6
-0.8
-1.0
-1.2
-1.4
-0.8
-1.0
-1.2
-1.4
-0.8
-1.0
-1.2
-1.4
4.0
5.0
6.0
7.0

Figure 29

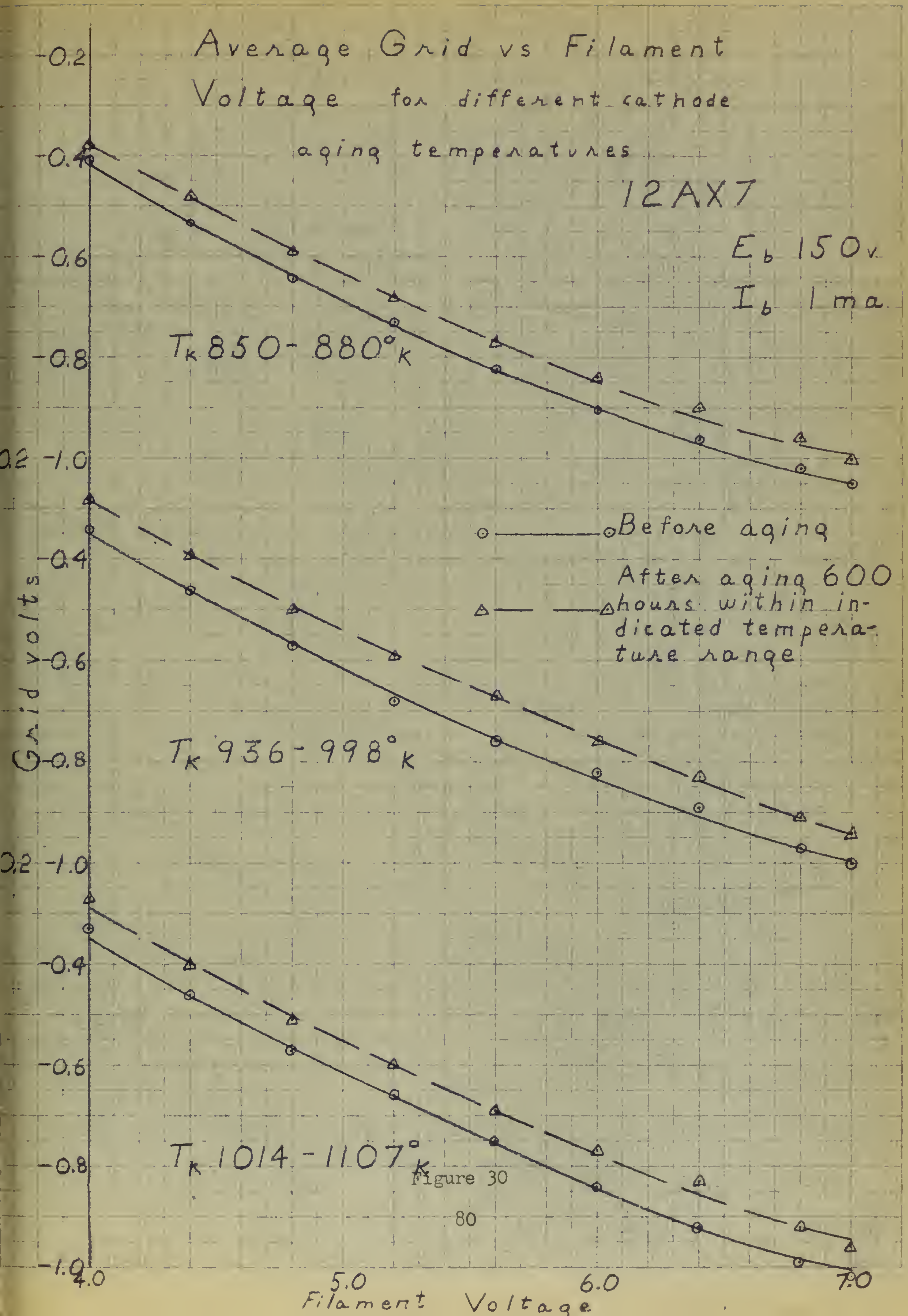

Average Grid vs Filament Voltage for different cathode aging temperatures
12AX7
E_b 150v
I_b 1 ma
T_k 850 - 880° K
T_k 936 - 998° K
T_k 1014 - 1107° K
Before aging
After aging 600 hours within indicated temperature range
Grid volts
-0.2
-0.4
-0.6
-0.8
-1.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.2
-0.4
-0.6
-0.8
-1.0
Filament Voltage
4.0
5.0
6.0
7.0

Figure 30

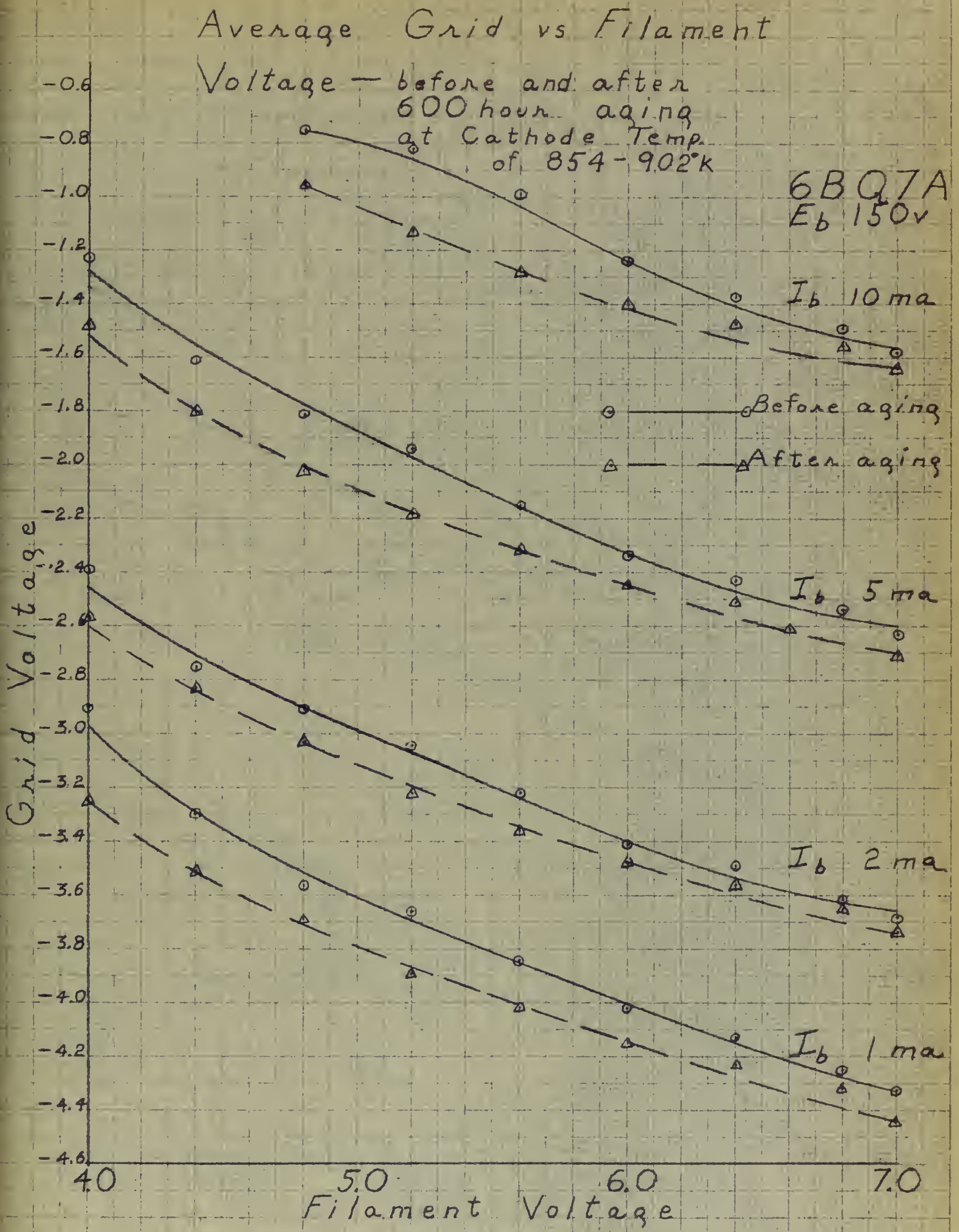
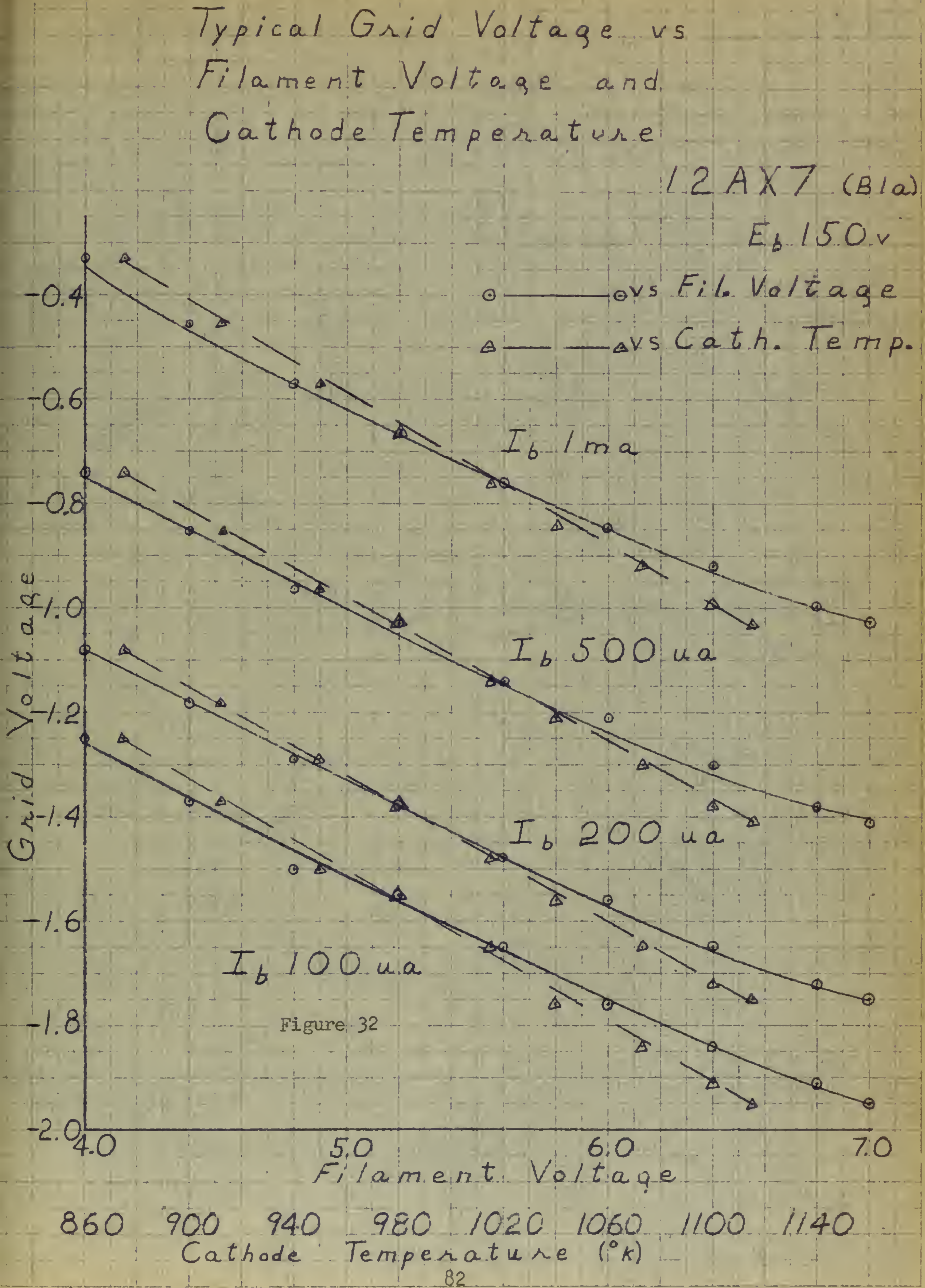
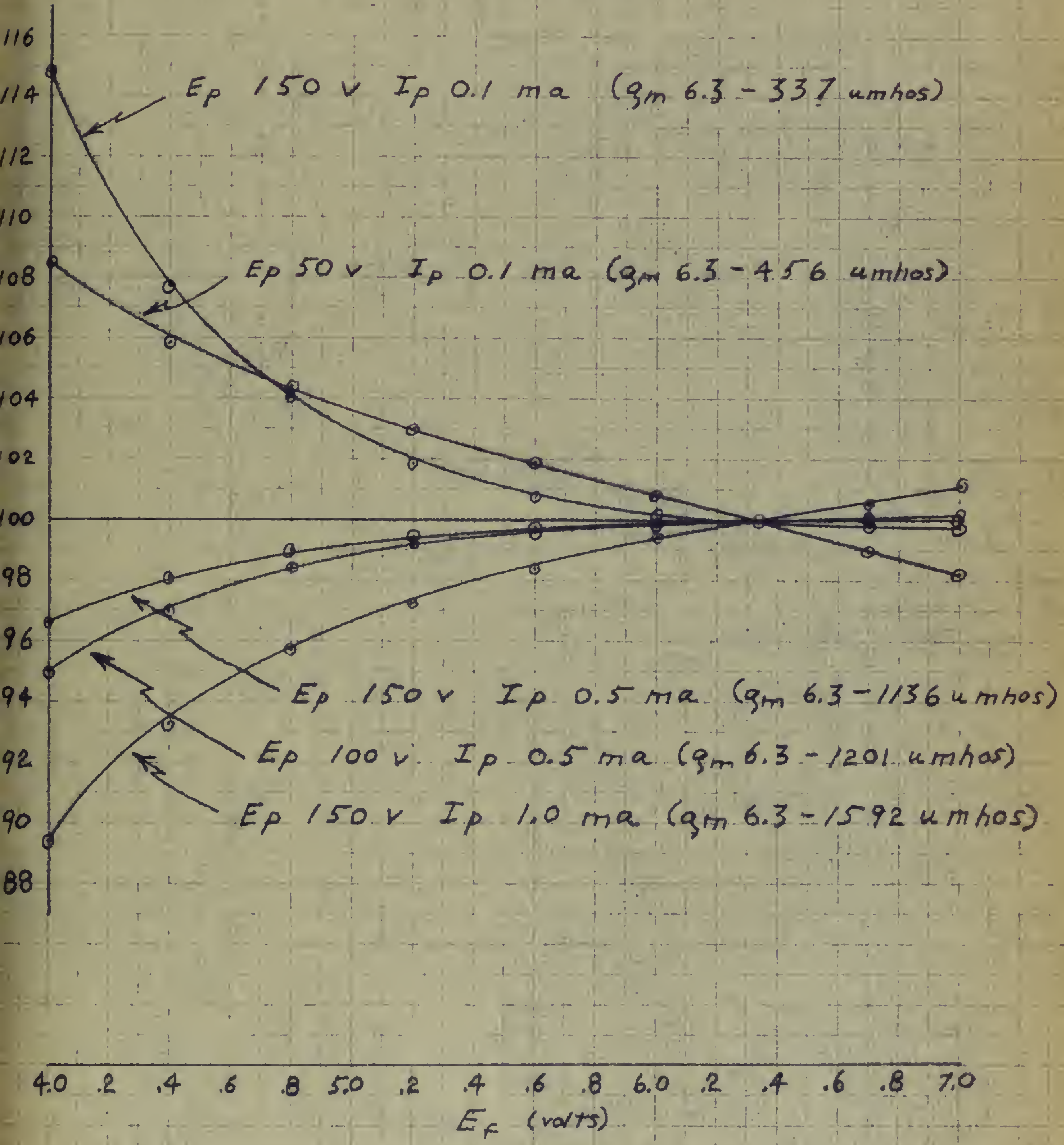

Average Grid vs Filament Voltage — before and after 600 hour aging at Cathode Temp. of 854-902°K
6BQ7A
Eb 150v
Ib 10ma
Ib 5ma
Ib 2ma
Ib 1ma
Before aging
After aging
Grid Voltage
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-2.2
-2.40
-2.6
-2.8
-3.0
-3.2
-3.4
-3.6
-3.8
-4.0
-4.2
-4.4
-4.6
4.0
5.0
6.0
7.0
Filament Voltage

Figure 31



Typical Grid Voltage vs Filament Voltage and Cathode Temperature

Figure 32


Average Percentage Variation of Transconductance with Filament Voltage

12AX7

Figure 33

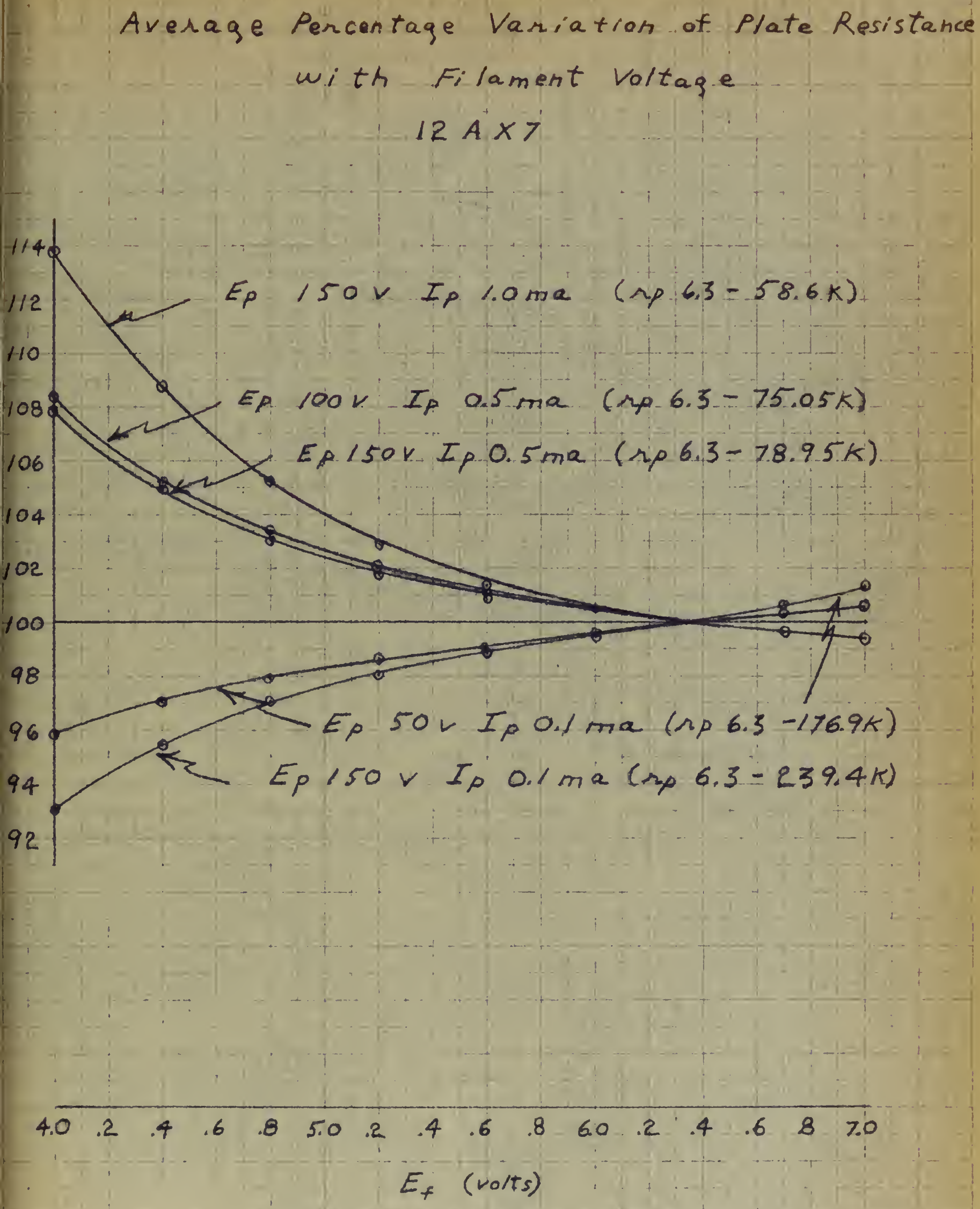

Average Percentage Variation of Plate Resistance
with Filament Voltage
12 AX7
114
112
110
108
106
104
102
100
98
96
94
92
Ep 150 v Ip 1.0 ma (rp 6.3 - 58.6 K)
Ep 100 v Ip 0.5 ma (rp 6.3 - 75.05 K)
Ep 150 v Ip 0.5 ma (rp 6.3 - 78.95 K)
Ep 50 v Ip 0.1 ma (rp 6.3 - 176.9 K)
Ep 150 v Ip 0.1 ma (rp 6.3 - 239.4 K)
4.0
.2
.4
.6
.8
5.0
.2
.4
.6
.8
6.0
.2
.4
.6
.8
7.0
Ef (volts)

Figure 34

Average Percent Variation of Amplification Factor with Filament Voltage

12 A X 7

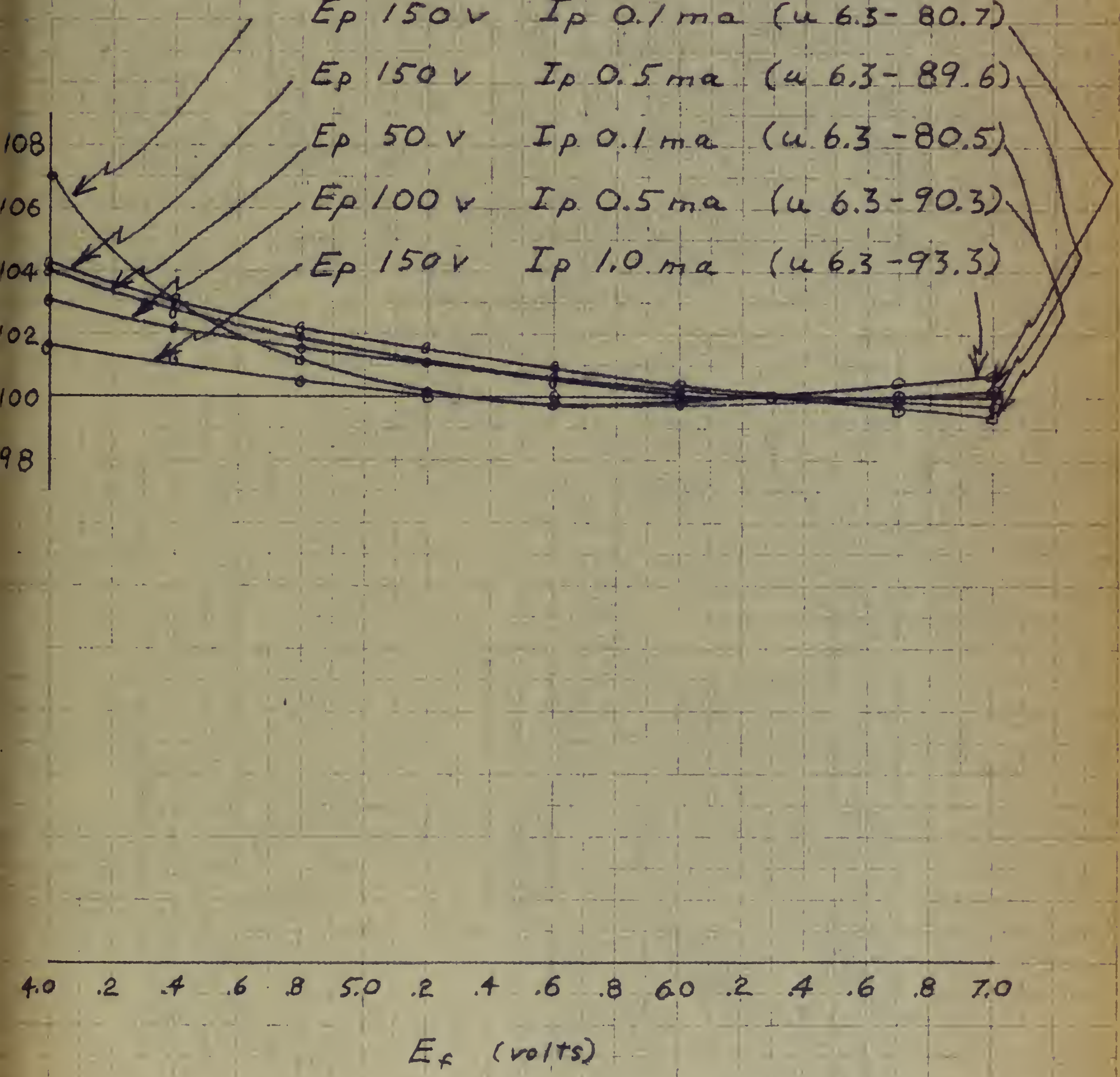


Figure 35

Values of plate resistance and transconductance were measured for all tubes before and after aging. While these values varied with the individual tubes, no relation between their variations and the growth of interface resistance or emission current was apparent. That no variation was apparent because of emission changes is in accord with the information given by Metson[39], that, under conditions of constant cathode current, a drop to 1% of original emission current will cause a drop of only 18% in transconductance. Comparisons were also made between average values of four tubes, for each half of the tubes, of grid voltage vs filament voltage for particular plate voltage and currents. There was no apparent difference between the averages of the separate sides of the tubes.

CHAPTER VIII

DISCUSSION OF RESULTS AND CONCLUSIONS

No tests were performed to give information on the effect of lowering the filament voltage on tube life as the time available did not permit. The curves given by the Bell Laboratories have been presented which give this information (Figures 9 and 10). From these curves alone the overwhelming advantages of increasing tube life with lower cathode temperature are apparent.

Next must be considered the variations of tube characteristics, both immediate and with time, with changing cathode temperature. Figures 23, 24 and 25 indicate that the tube characteristics will have the same relationship to grid voltage except for a constant value for the filament voltages considered here. Thus, except for a change in bias voltage the tubes will have the same characteristics for constant plate voltages. This change in bias effect noted above is also apparent in Figure 26. Figures 11, 12 and 13, by Mr. Winter, indicate that there will be little change of characteristics with changes of plate current for fixed plate voltage over the ranges of filament voltages (4.3 to 6.3v) considered here.

Considering the changes of characteristics with time, Figure 26 indicates that at least over the limited time of these tests the characteristics did not change appreciable. It is to be noted that

the variation of plate current for fixed values of grid and plate voltage among the four tubes used here did decrease during the time of the test for the lower filament voltage. Before aging the variation, at 1.2ma plate current and a filament voltage of 6.3v, was 16.7% — after the aging the variation was unchanged. Before aging the variation, at 1.2ma plate current and a filament voltage of 5.1v, was 24.2% — after the aging the variation was 13.3%. Thus there was an improvement of 3.4% over the 6.3v and an improvement of 10.9% over the 5.1v. Further tests should be conducted to determine whether this improvement will continue.

Figures 27, 28, 29 and 30 show how the grid voltage will vary for fixed values of plate voltage and current with changing filament voltage. Curves are given here for the conditions both before and after aging. It is to be noted that the shapes of all the curves are the same, and, as expected from the above discussion, the variations of grid voltage with aging were less at the lower aging temperatures, especially at the lower plate currents. Figure 31 gives the same data, as the above figures, for the 6BQ7A tubes. These curves show that their shape is not necessarily a function of tube type and is relatively independent of plate current. Figure 32 gives typical curves of grid voltage as a function of filament voltage and cathode temperature. Here the almost linear relationship between grid voltage and cathode temperature is apparent.

Figures 33, 34 and 35 indicate that where any variation of tube characteristics with filament voltage is important, as perhaps in

precision amplifiers and voltage regulators, there exists an optimum combination of plate voltage and current where, with wide variations of filament voltage, no change of one or the other of transconductance or plate resistance will occur.

With regards to the possibility of a short time test to provide information for predicting relative tube life, Figures 20 and 21 and Tables IIIA, IIIB and IV indicate only that definite trends of interface resistance and emission do develop in this time. In these tests all of the tubes performed similarly to the others in its temperature range. If one or more of the tubes had shown a radical departure from the average, this tube could probably be judged as to a longer or shorter life expectancy with respect to the others depending on the direction of departure. To establish this test, further aging must be performed. Considering the growth of interface resistance, it would probably be advantageous to age the tubes at higher filament voltages and under no-plate-current conditions. In order to establish the usefulness of this test it must be ascertained that the individual tube is characteristic of its particular manufacturing lot. This is yet to be done. The curves of relative cathode emission present some unexpected data. Considering the activating and poisoning phenomena, the emission would be expected to increase as the cathode temperature increased. This was not the case with the tubes tested. There is no ready explanation by the writer of the observed data at this time. This information can be compared with the results obtained by Wagener[62] and presented in the table on page twelve. It is noted that at the

lower aging temperature, the emission density increased noticably over that at the higher aging temperature. This effect is not discussed in this or subsequent references. The tremendous spread of emission values is worthy of note. At least in the case of the 6BQ7A tube type, operation under conditions of high peak or average plate currents will not permit an indiscriminate choice of tubes.

The results of the noise investigation indicate that there is a possibility of tube noise reduction at the lower cathode temperatures. The tests conducted were not exhaustive enough to permit further conclusions to be drawn.

CHAPTER IX

SUMMARY AND RECOMMENDATIONS FOR FURTHER INVESTIGATION

From the above information several conclusions can be obtained.

(1) From the curves of Bell, the life of vacuum tubes will be increased by operating them at lower cathode temperatures.

(2) Provided the cathode temperature is not reduced lower than some 800°K, the characteristics of the tubes will not change appreciably.

(3) The effect of changing cathode temperature can be represented by a dc voltage generator in the grid circuit of a value of -2.375×10^{-3} volts per degree change of absolute cathode temperature for the 12AX7 tube type.

(4) Variations of plate current with time will be reduced by operating at lower cathode temperatures.

(5) The basis of a short time tube life test is presented and no information was uncovered which might refute it. The information obtained was not sufficient to definitely establish the test.

(6) There is a possibility of tube noise reduction at lower cathode temperatures.

(7) There is a possibility of decreased tube life due to cathode poisoning in some modern ruggedized tubes because of the

increased mica spacers used.

With the above conclusions in view, it is believed that further study of these problems is warrented. First, complete life tests should be run to determine if the usual variations of cathode temperatures of commercial tubes are related to their individual lives. During these tests variation between and within the manufacturers tube lots would be apparent. During this aging for the first thousand hours, interface resistance and relative emission investigations should be carried out in an attempt to correlate the information thus obtained with life and variation of tube characteristics with time. Second, further investigation of the relationship between tube noise, both wide band Johnson noise and the low frequency flicker noise, and cathode temperature should be conducted. Third, an investigation of the increase of emission with lower cathode temperature aging should be conducted.

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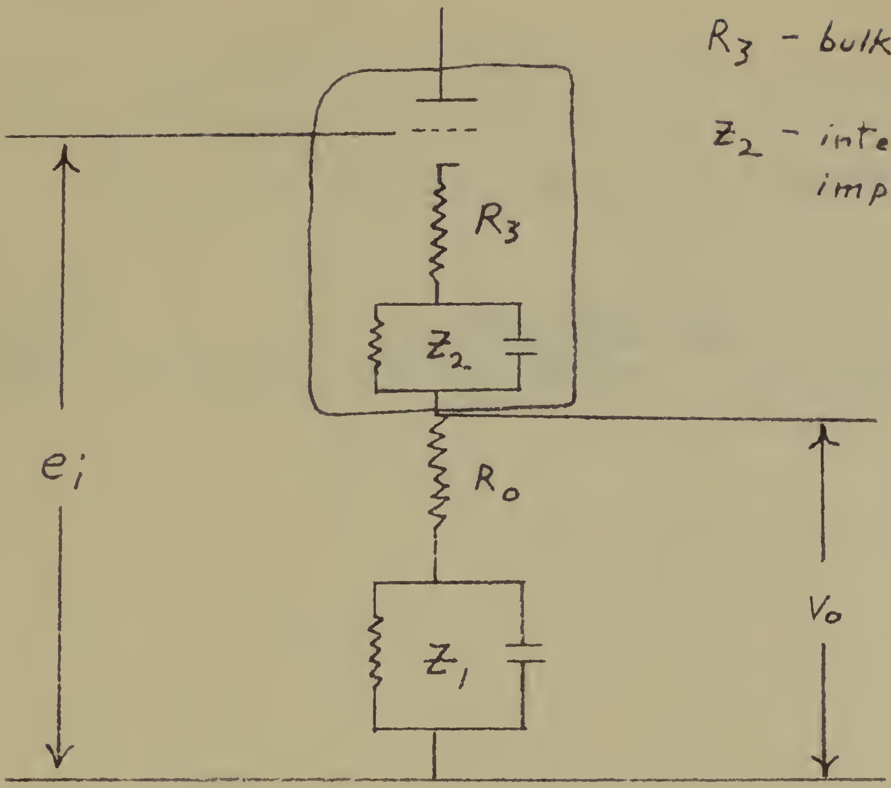
Appendix A



R_3 - bulk resistance

Z_2 - interface impedance

$$\Delta i_b = g_m \Delta e_c + \frac{1}{r_p} \Delta e_b$$

$$\Delta e_c = \Delta e_i - \Delta i_b (R_3 + Z_2 + R_o + Z_1)$$

$$= \Delta e_i - \Delta i_b (R_3 + Z_2) - \Delta V_o$$

$$\Delta e_b = - \Delta i_b (R_3 + Z_2 + R_o + Z_1)$$

$$= - \Delta i_b (R_3 + Z_2) - \Delta V_o$$

$$\Delta i_b = g_m [\Delta e_i - \Delta i_b (R_3 + Z_2) - \Delta V_o] -$$

$$1/r_p [\Delta i_b (R_3 + Z_2) - \Delta V_o]$$

$$\Delta V_o = \Delta i_b (R_o + Z_1)$$

$$\Delta V_o = g_m(\Delta e_i - \Delta V_o)(R_o + Z_1) - g_m \Delta V_o (R_3 + Z_2)$$

$$- \frac{1}{r_p} \Delta V_o (R_o + Z_1) - \frac{1}{r_p} \Delta V_o (R_3 + Z_2)$$

$$\frac{\Delta V_o}{\Delta e_i} = \frac{g_m(R_o + Z_1)}{1 + g_m(R_o + R_3 + Z_1 + Z_2) + \frac{1}{r_p}(R_o + R_3 + Z_1 + Z_2)}$$

28456
Thesis
J638
Johnson
Effect of oxide-coated cathode temperature variation in vacuum tubes.

23456
Thesis
J638
Johnson
Effect of oxide-coated cathode temperature variation in vacuum tubes.

thesJ638
Effect of oxide-coated cathode temperatu
3 2768 002 10536 3
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